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AN EXPERIMENTAL STUDY OF PRESSURE WAVES IN GUN CHAMBERS

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U. S. Naval Proving Ground
Dahlgren, Virginia

An Experimental Study of Pressure Waves in Gun Chambers

by

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and
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Weapons Development and Evaluation Laboratory

NPG REPORT NO. 1534

Task Assignment No.
NPG-S6-2d-2-1-56
and
Foundational Research
Project NPG-W-1802-4

25 April 1957

APPROVED: G. H. WALES
Captain, USN
Commander, Naval Proving Ground

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CONTENTS

ABSTRACT

Experimental studies of the space-time variations in pressure in gun chambers leads to the conclusions that pressure waves are manifestations of standing pressure waves in the propellant gases and that these waves develop as a result of pressure gradients set up in the chamber in the initial stages of the pressure cycle in combination with motion and differential packing of the propellant produced by the gradients.

FOREWORD

The phase of the study concerned with the nature of pressure waves was carried out under Task Assignment NPG-S6-2d-2-1-56, "Gun Propellant Ignition Studies", authorized by reference (a). This phase of the study is treated here in essentially the form in which it was originally presented at the Seventh AXP Tripartite Conference (reference (b)) and again later in the preprints of the Second Symposium on Solid Propellant Ignition (reference (c)). The second phase of the study, dealing with the origin of pressure waves, was carried out under Foundational Research Project NPG-W-1802-4, "Pressure Waves in Propellant Gases", authorized by reference (d)). This phase of the study was presented in outline at the Second Symposium on Solid Propellant Ignition (reference (c)) and is presented here in expanded form.

This report was reviewed by the following personnel of the Weapons Development and Evaluation Laboratory.

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and by

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INTRODUCTION

In the literature pertaining to pressure waves in gun chambers, these waves are almost invariably attributed to "sporadic burning" of the propellant, with the implication that an erratic and uncontrolled mode of burning is involved in the formation of pressure waves. This conception leads, understandably, to the attitude that the presence of pressure waves indicates a potentially dangerous condition; that any chance round may develop a dangerously high pressure in the gun chamber. A second attitude, that muzzle velocity is more variable from rounds producing pressure waves than from similar rounds producing smooth pressure curves, seems also to result from the "sporadic burning" concept of pressure waves. The studies conducted at the Naval Proving Ground on the nature and origin of pressure waves does not support the "sporadic burning" theory of pressure waves, removes much of the cause for considering these waves as potentially dangerous, and indicates that pressure waves are not to be considered prime sources of velocity variation.

The study of pressure waves in gun chambers which has been carried out at the Naval Proving Ground divides into two phases. The first phase was concerned primarily with establishing the nature of these waves and led to the formulation of the standing wave hypothesis of pressure waves. The second phase, which grew out of the first as a logical continuation of the study, has been concerned with the manner in which pressure waves originate and develop in gun chambers. Though it is not considered that this latter phase has been studied exhaustively, the work to date has led to an identification of the more important parameters involved in the origin and development of pressure waves, has shown the manner in which two of these parameters may interact in forming waves, and has permitted the formation of a working hypothesis of the mechanisms by which pressure waves originate in gun chambers. The two phases of the study will be treated in the order in which they were chronologically pursued.

THE NATURE OF PRESSURE WAVES

The nature of pressure waves was deduced from a study of the space-time variations in pressure in several gun chambers. Pressure-time curves obtained simultaneously at two to five positions in the gun chambers constituted the basic data. Data of this type were accessible from two conventional naval guns, one hypervelocity experimental gun, and a gun-simulator commonly referred to as a "blow-out" gun. Pressure curves exhibiting well-defined pressure waves were available for study from each of these guns. In all of the examples studied, it was found that the space-time relations of the pressure waves could be interpreted on the hypothesis of a standing pressure wave in the propellant gases. Typical samples of the experimental evidence forming the basis for this hypothesis follow.

We will consider first a typical set of pressure records from the blow-out gun in which the standing wave character of the pressure waves is somewhat more explicitly demonstrated, because the chamber of this device remains fixed in length during the entire pressure cycle.

The blow-out gun was manufactured at the Naval Proving Ground as an experimental device for studying the ignition and early burning of propellants. A 5"/38 caliber gun barrel was cut off approximately 9.5 inches forward of the origin of the bore and modified in such a way that an orifice could be installed at the position corresponding to the base of a seated projectile in the normal gun. Three pressure gauges were installed in the chamber wall to measure chamber pressures. One gauge was located at the center of the chamber, one three inches forward of the breech face, and the third three inches aft of the orifice. Any type of charge which can be made up in a standard 5"/38 case can be fired in this device. With the proper choice of orifice diameter, the pressure histories recorded at the three gauge stations in the blow-out gun are similar in space and time relations to those obtained in the conventional gun firing a like charge. The advantages of the blow-out gun are that the maximum pressures are only about half those obtained in a conventional gun and that no projectile is required. The general similarity of the pressure histories recorded in the blow-out gun to those of a standard gun will be seen in comparing Figures 1 and 2. By duplicating the chamber length of a 5"/54 caliber gun (by moving the orifice forward six inches) the blow-out gun reproduces equally well the pressure histories obtained in the 5"/54 gun.

A set of blow-out gun pressure records with pronounced pressure waves is presented in Figure 1. This set was obtained in the firing of a standard 5"/38 service charge ignited with a primer venting in the forward section of the charge. Descriptively, we have here pronounced waves on the records from the two ends of the chamber with the compressions and rarefactions 180° out of phase at the two ends. But no comparable waves are present on the record from the center of the chamber. In Figure 1A we have plotted only the wave components of the pressure curves shown in the first figure. These curves were obtained by taking the difference between the three pressure records and a smooth curve drawn through the points of equal pressure on the three pressure curves. This wave pattern immediately suggests a standing wave mode of vibration. Further consideration shows that a standing wave in a tube closed at both ends vibrating at the fundamental frequency of the tube would give this wave pattern and would also be consistent with further deductions we can make.

Since there is a sudden reduction in diameter of the blow-out gun chamber at the orifice, a wave in the chamber would be partly reflected without change in sign at the orifice. In the firing considered here, the orifice effected a 56% area closure of the chamber. Therefore the orifice should function in part as a closed end. The damping of the wave can be attributed, at least in part, to the fact that there is only partial reflection of the wave at the orifice.

Several considerations make it probable that the vibration is at the fundamental frequency of the chamber. In the early part of the pressure cycle, the velocity of the wave in the chamber can be expected to be close to that of the velocity of sound in air. If we calculate the wave velocity assuming a wave length twice that of the chamber (the fundamental wave length) and determine the period of the wave for the first quarter-cycle of the first pressure oscillation on the pressure records, we obtain a

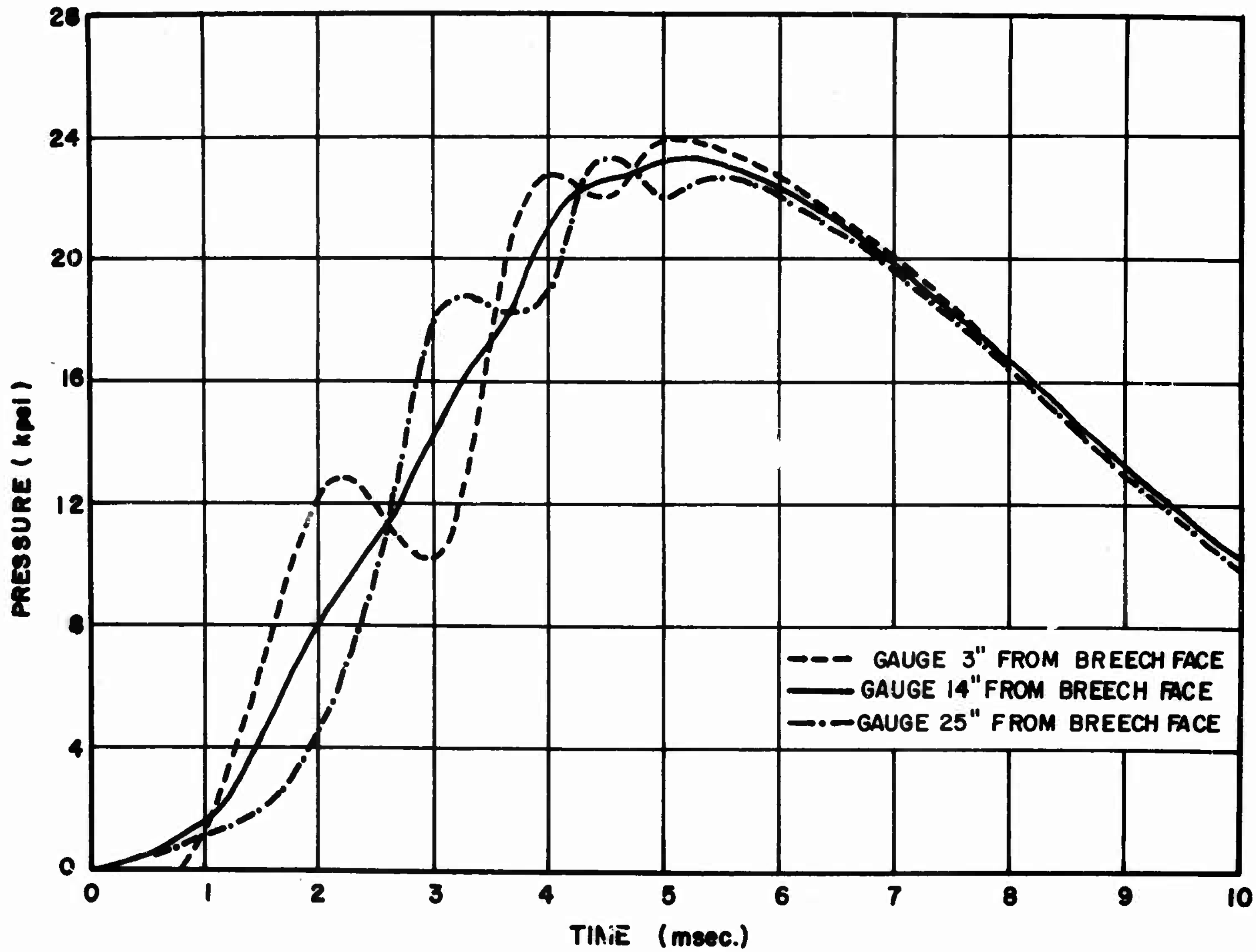

FIGURE 1. PRESSURE-TIME CURVES FROM 5"/38 BLOW-OUT GUN

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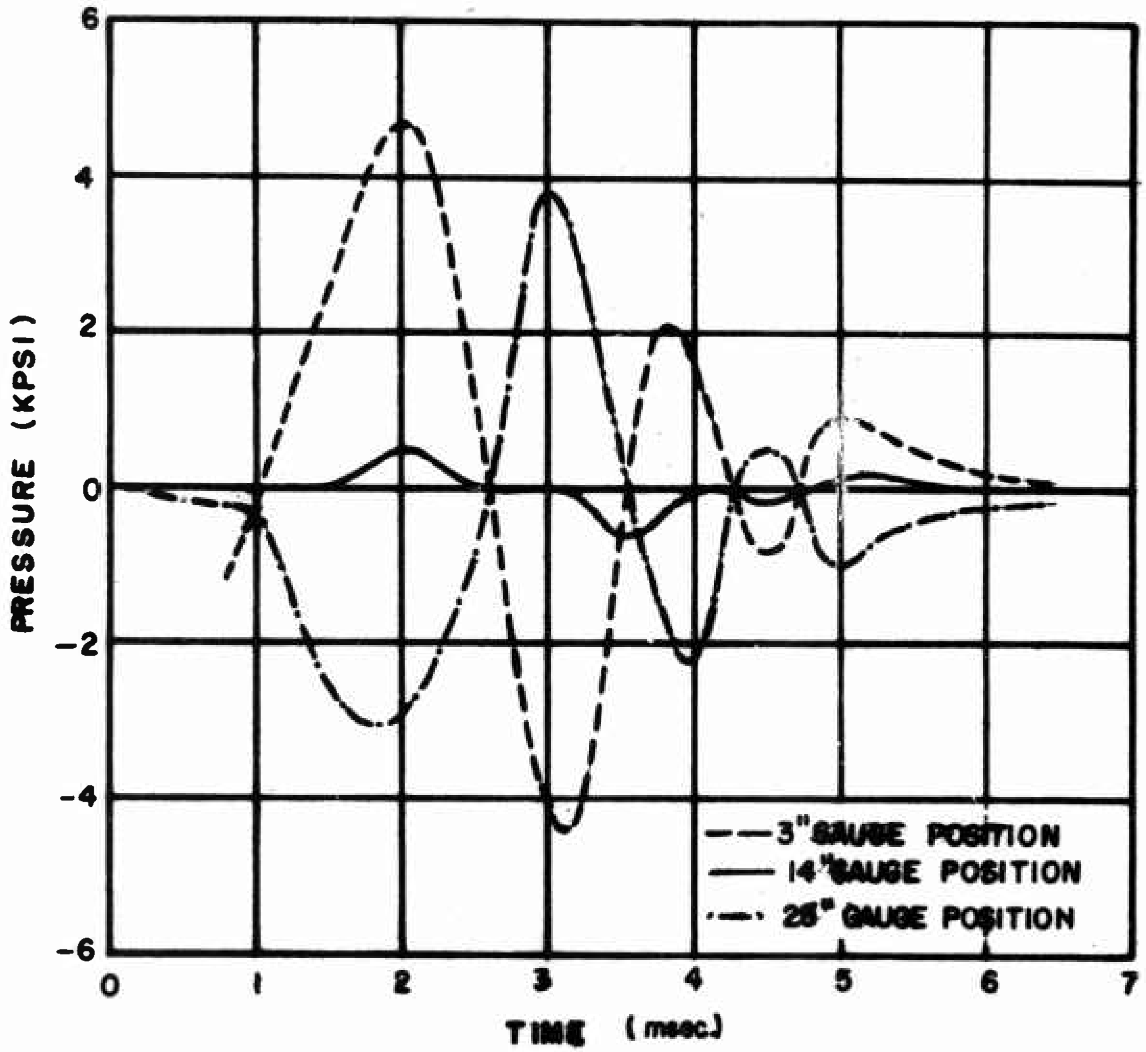

FIGURE IA PRESSURE WAVES IN 5"/38 BLOWOUT GUN

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velocity of about 1200 ft/sec. Using the period for the first half cycle instead, we obtain 1550 ft/sec for the velocity. We of course expect the propagation velocity to increase as the pressure rises as a result of the changes taking place in the medium. If the vibrations represented a harmonic instead of the fundamental, the computed velocities would come out one-half, one-third, etc. of the above values, depending on the harmonic selected.

We can also rule out all even harmonics since any of these would produce compressions and rarefactions simultaneously at both ends of the chamber and the opposite conditions (rarefactions and compressions) at the center of the chamber. Pressure records at stations midway between the center gauge and end gauges show waves with amplitudes somewhat less than those recorded at the ends of the chamber, and in phase with the vibrations at the ends. The third harmonic would produce wave action at these intermediate gauge stations approximately 90° out of phase with that at the end gauges and at approximately twice the amplitude. The fifth harmonic would produce antinodes at approximately the positions of all five gauge stations.

Let us now consider a set of pressure curves from a conventional 5"/38 gun. A typical set of records from this gun is shown in Figure 2. The powder, charge weight, and igniter were the same as those used to obtain the blow-out gun records considered above, and the pressures were recorded at approximately the same positions in the chamber (3, 15 and 23 inches from the breech face as compared to 3, 14 and 25 inches in the blow-out gun). The general similarity of the wave pattern exhibited by this set of records to that of the set from the blow-out gun in Figure 1, particularly in the early stages, is at once evident.

In Figure 2A we have plotted only the wave components of the pressure curves shown in the previous figure. These curves show the differences between the three pressure records and a smooth curve drawn through the points of equal pressure on the three pressure curves.

In Figure 3 we have shown the relative wave amplitudes from the previous figure on a space-time plot. The projectile travel curve included on the plot was obtained by integrating twice a projectile acceleration curve computed

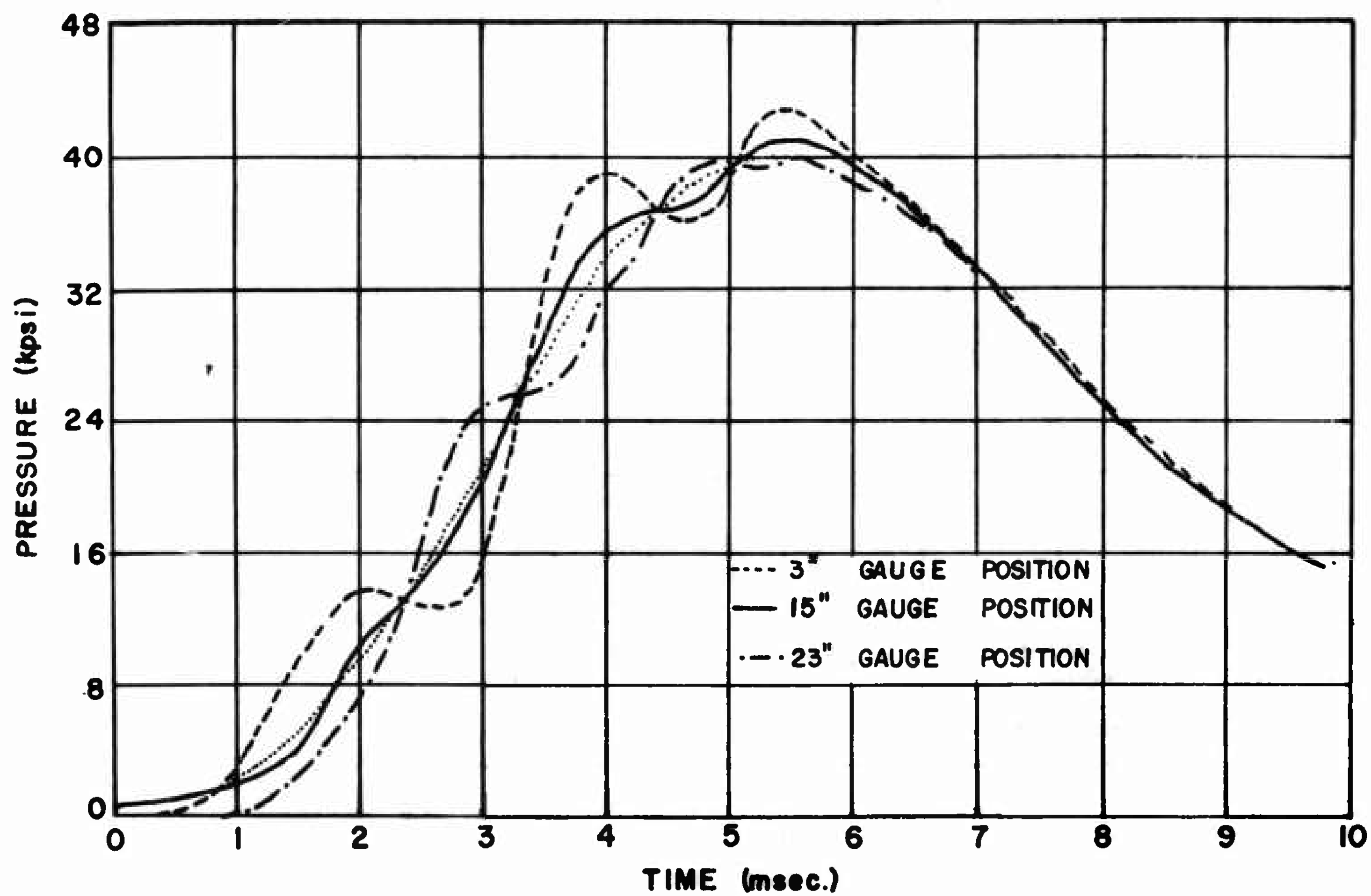

FIGURE 2. PRESSURE-TIME CURVES FROM 5"/38 GUN

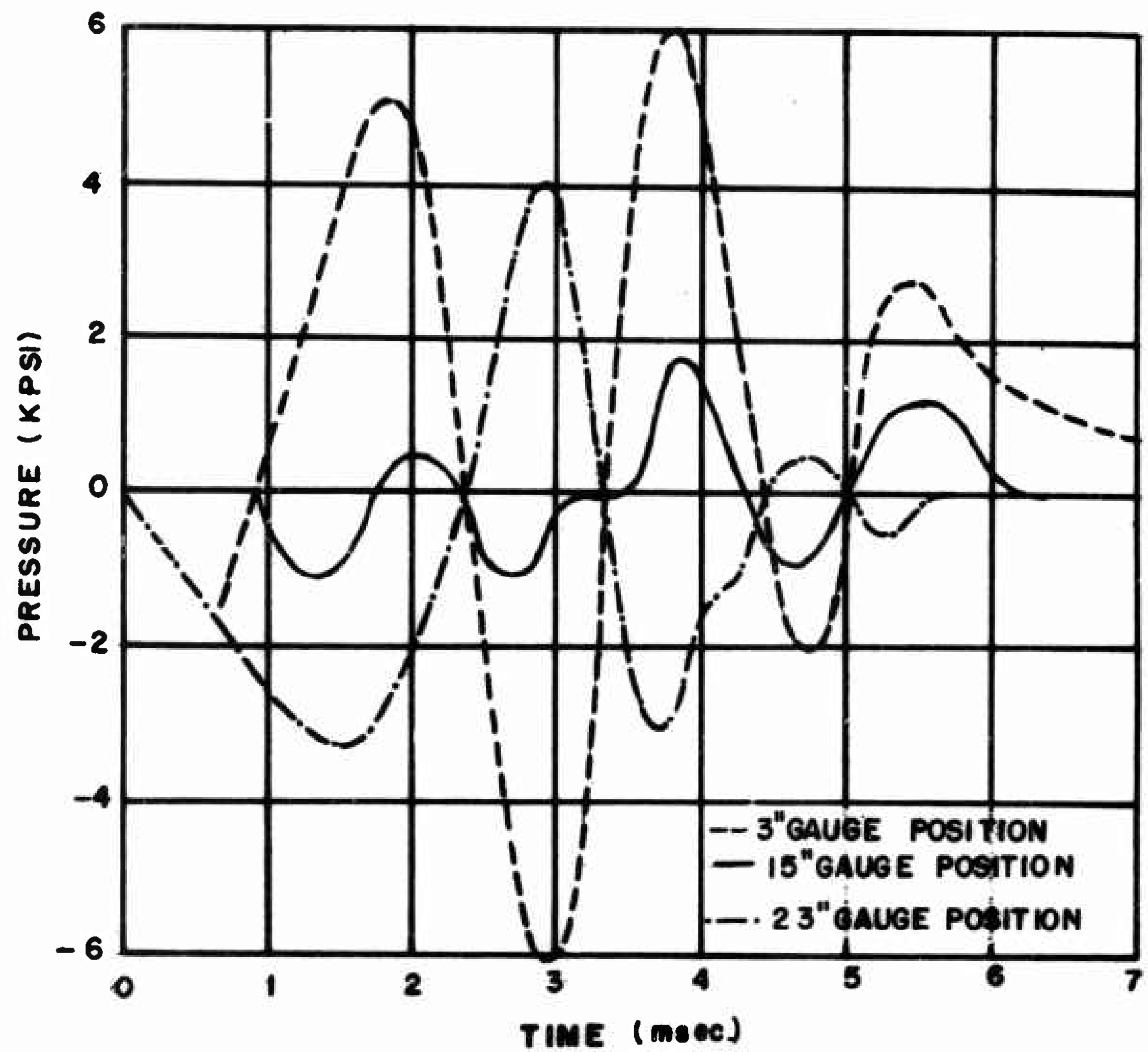

FIGURE 2A. PRESSURE WAVES IN 5"/38 GUN

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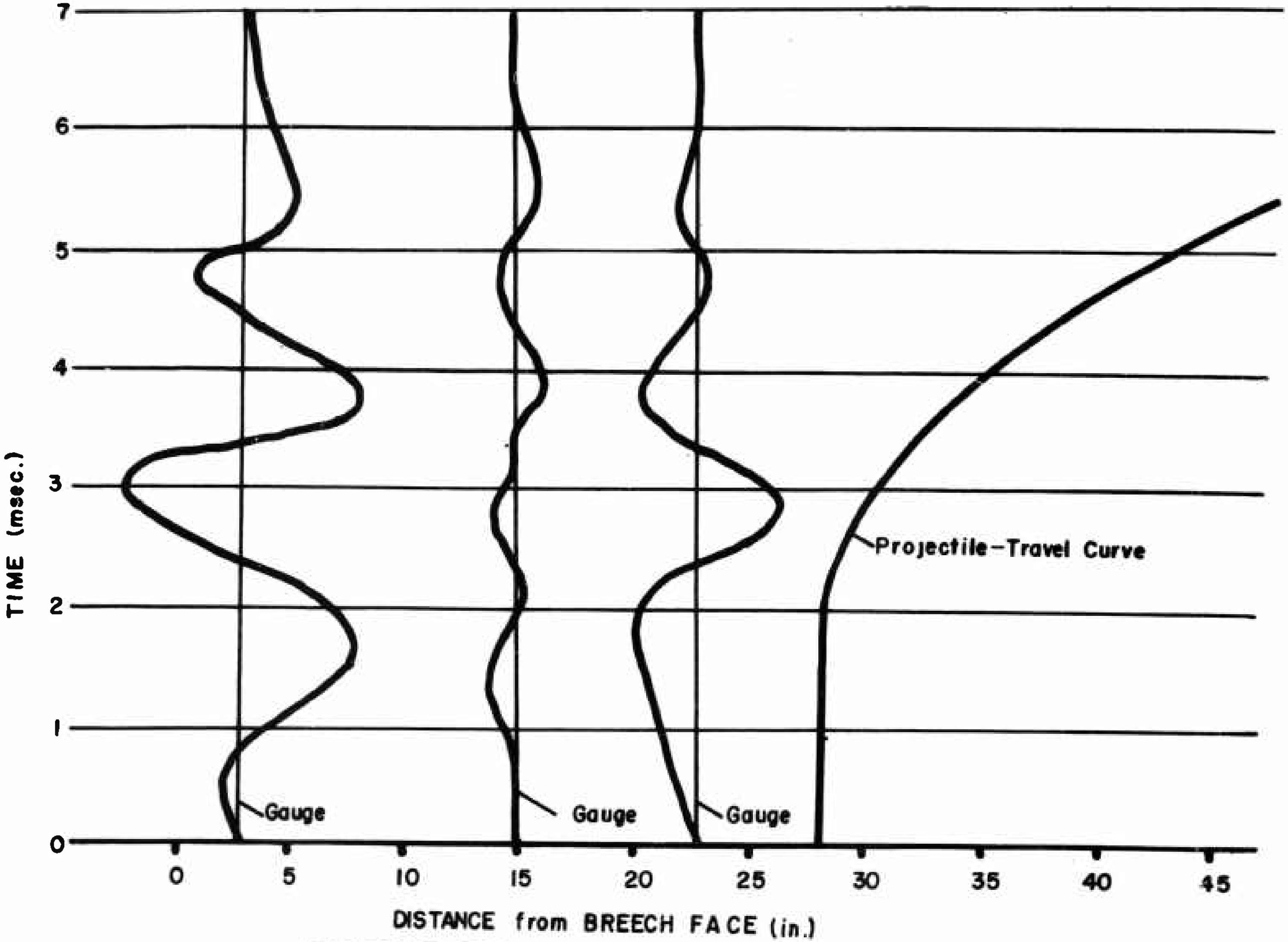

FIGURE 3. PRESSURE WAVES IN 5"/38 GUN

Compressions are to right and Rarefactions to left of vertical lines

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from the average chamber pressure. While this travel curve is only an approximation, it is in close agreement at maximum pressure with the projectile motion computed by the Hunt-Hinds System, and is sufficiently realistic for our present purposes.

These waves also can be interpreted as the result of a standing wave mode of vibration in the gun chamber if the increase in chamber length accompanying the forward motion of the projectile is taken into account. In Figure 3 it will be observed that as the propellant gas column increases in length, oscillations appearing on the center gauge become in phase with those on the rear gauge, but that the amplitudes of these oscillations are less than those at the rear gauge position.* On the other hand, the oscillations at the forward gauge decrease in amplitude during this time and practically disappear at the time this gauge becomes about half way between the base of the case and the base of the projectile. All of these observations are in accord with the results to be expected from a standing wave in a tube increasing in length with time. It appears in this case that only a vibration at the fundamental frequency of the chamber can give us the wave pattern we observe on the center and forward gauges as these are, in effect, moved rearward as the propellant column expands in length. The condition here is analogous to that of a standing wave on a spring which is fixed at one end, but is being extended at the other end. That the wave motion is able to expand into the total space behind the projectile appears plausible in view of the fact that in this gun there is practically no change in diameter between the chamber and the bore of the gun. As will be noted later, this extension of the standing wave does not appear to occur in a gun with pronounced chambrage.

*We cannot account for the small oscillations occurring on the center gauge record in the early part of the pressure cycle. They may possibly represent only an oscillation of the antinode position. There is a definite change in frequency and phase at the time considered above, however.

We have also studied the space-time relations of the waves observed on pressure-time records from 5"/54 blow-out gun and 5"/54 gun firings. The data from these two guns were in agreement in all essential aspects with the interpretations made of the 5"/38 data. To consider it further here would only lead to a repetition of what we have already stated above. We may point out, however, that the 5"/54 gun is similar to the 5"/38 in that it does not have a pronounced chambrage.

Let us next consider the pressure waves observed on a 4"/3" gun firing. This gun was designed as a hypervelocity squeeze-bore gun, but the firings considered here were made without the 3" bore section attached to the 4" barrel. A typical set of pressure records obtained from the chamber and several positions along the bore is presented in Figure 4. Applying the same general method of analysis to this set as was used on the 5"/38 gun records, we obtained the wave patterns shown in Figure 5. We have included the waves from only the first three bore positions here. The projectile travel curve in this case was determined from the pressure records along the barrel.

The wave pattern we have here appears to be that of a standing wave in the chamber, but of a traveling wave in the bore of the gun. If we consider the chamber geometry of this gun, we see that a wave action of this nature is plausible with this geometry. This gun has pronounced chambrage, there being a decrease from a diameter of seven inches to four inches at the forward end of the case (see Figure 5). A wave originating in the chamber would, upon reaching the necked-down section, be partly reflected and partly transmitted. A standing wave mode of vibration could then be set up in the chamber by the reflected part of the wave while the transmitted part would travel down the bore as a progressive wave. The restriction in the case here appears to operate in a manner similar to the orifice in the blow-out gun and as wave theory indicates it would.

While we have presented here only one set of pressure records from each gun system under study, these sets are typical in as much as they are reproducible on repeated firings.

Thus, in the five gun systems we have considered, the space-time relations of the pressure waves, as revealed by simultaneous pressure-records at several positions in the

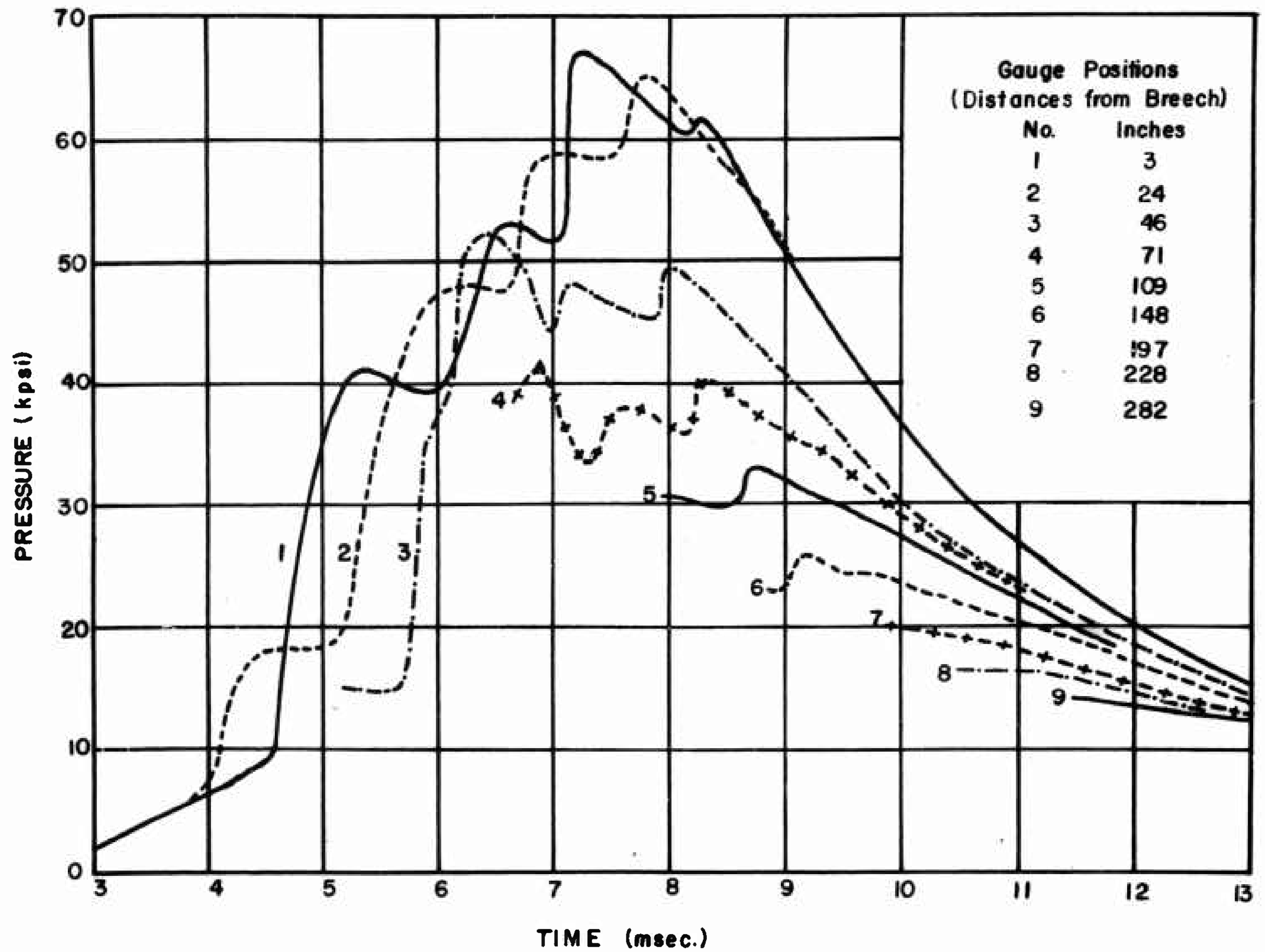

FIGURE 4. PRESSURE-TIME CURVES FROM 4.3" EXPERIMENTAL GUN

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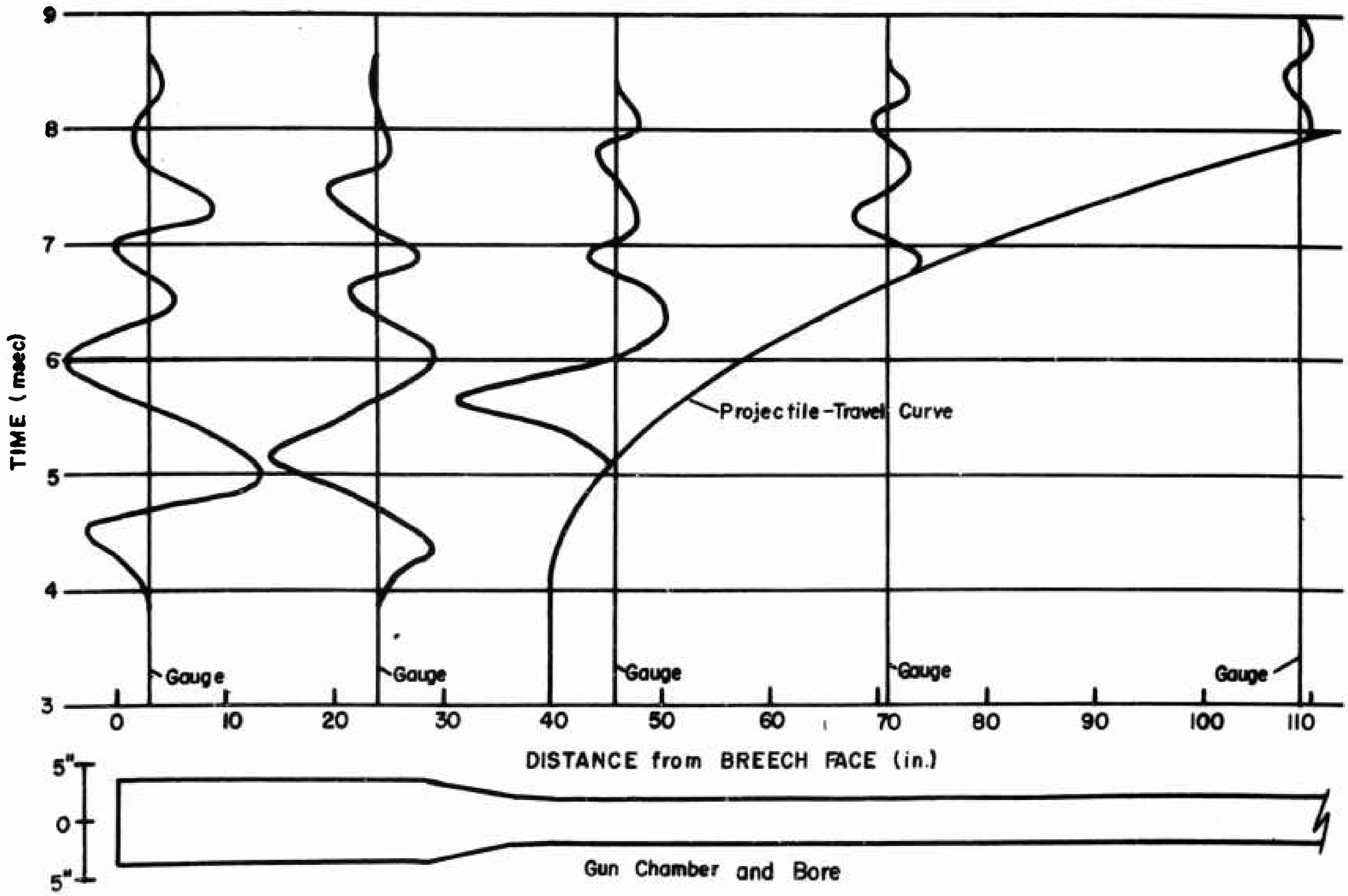

FIGURE 5. PRESSURE WAVES IN 4⅐3" EXPERIMENTAL GUN

Compressions are to right and Rarefactions to left of vertical lines

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gun chambers, support the conclusion that these waves are manifestations of standing pressure waves in the propellant gases.

This interpretation of pressure waves implies that "roughness" of propellant burning is a space-dependent variable and has practical applications for the propellant evaluator. If we are interested in the degree of "roughness" of the pressure curve, we should locate our pressure gauge near the breech end of the gun chamber because the manifestations of "roughness" will be most pronounced in this region. On the other hand, if we are more interested in mean chamber pressures, we would do well to locate our gauge near the center of the chamber and thereby obtain pressure curves relatively free of oscillations. Gauges located near the base of the seated projectile would give data pertinent to shot-start pressure and early projectile motion.

THE ORIGIN AND DEVELOPMENT OF PRESSURE WAVES

While the standing wave hypothesis of pressure waves describes the nature of these waves, it does not explain the manner in which they originate and develop in gun chambers. A theory of the mechanisms by which standing pressure waves originate in gun chambers is a prerequisite, first, to an evaluation of the ballistic significance of these waves, and second, to the control of these waves in practical ballistic applications.

Since pressure waves are, fundamentally, oscillatory pressure gradients, these waves must arise from pressure gradients set up in the gun chamber which, under proper conditions, become oscillatory and develop into standing waves. The problem of the origin of pressure waves thus resolves into one of identifying the sources of these initial pressure gradients and of explaining the manner in which they develop into standing pressure waves. A considerable volume of pressure-time data from a wide variety of test firings carried out at the Naval Proving Ground was reviewed from this point of view. While these data suggested a number of parameters which might contribute to initial pressure gradients in the gun chamber, the parameters which appeared to be most pertinent for further study were (1) the axial position within the charge at which the propellant was first ignited, and (2) the ullage or free space above charges which did not fill the available chamber volume. In connection with both of these parameters, it was observed that the rate of pressure rise increased with increasing distance through the chamber from both the point of ignition and the ullage. These differential rates of pressure rise through the chamber thus appeared to be sources of pressure gradients which might develop into standing pressure waves in the gun chamber.

The effect of point of ignition on the pressure history is illustrated by the pressure-time curves in Figure 6. We have shown here three pressure-time curves recorded at the breech end of the chamber in the firing of three rounds in a 3"/70 caliber gun. One round was ignited by approximately point source ignition near the rear of the chamber, the second was ignited near the center of the chamber, and the third near the forward end of the chamber. The rounds were otherwise identical and the propellant completely filled the case. We note, first, that the two end-ignited rounds produced pronounced pressure waves, while wave action is completely absent in the center-ignited round. Second, we note that the wave patterns from the two end-ignited rounds are 180° out of phase. Reversing the point of ignition also reverses the phase of the wave. The wave pattern formed by these two pressure records is identical to that to be expected from the two ends of the chamber from a single round ignited at one end of the chamber.

An effect of the configuration of the ullage on the pressure history is illustrated by the pressure-time curves of Figures 7 and 8. In Figure 7, the pressure curve with the pronounced pressure wave was recorded at the breech end of a 3"/50 caliber gun during the firing of a service charge of a slotted-tube propellant. There was a rather large ullage, equal to about one-third the total case volume, at the forward end of the case in this round. When this equivalent ullage volume was distributed longitudinally along one side of the case (and thereby producing a uniform axial distribution of the powder in the case) the smooth curve of Figure 7 was obtained. This uniform axial distribution of the powder was maintained during handling of the round by inserting a foam plastic rod of the proper dimensions along the periphery of the case before pouring the powder. Mk 42 primers were used in both rounds. Hollow pyralin cylinders were as effective as the foam plastic rods in eliminating the pressure waves. Similar results were obtained with a deterrent-coated powder. Two pressure curves from the firing of this powder in a

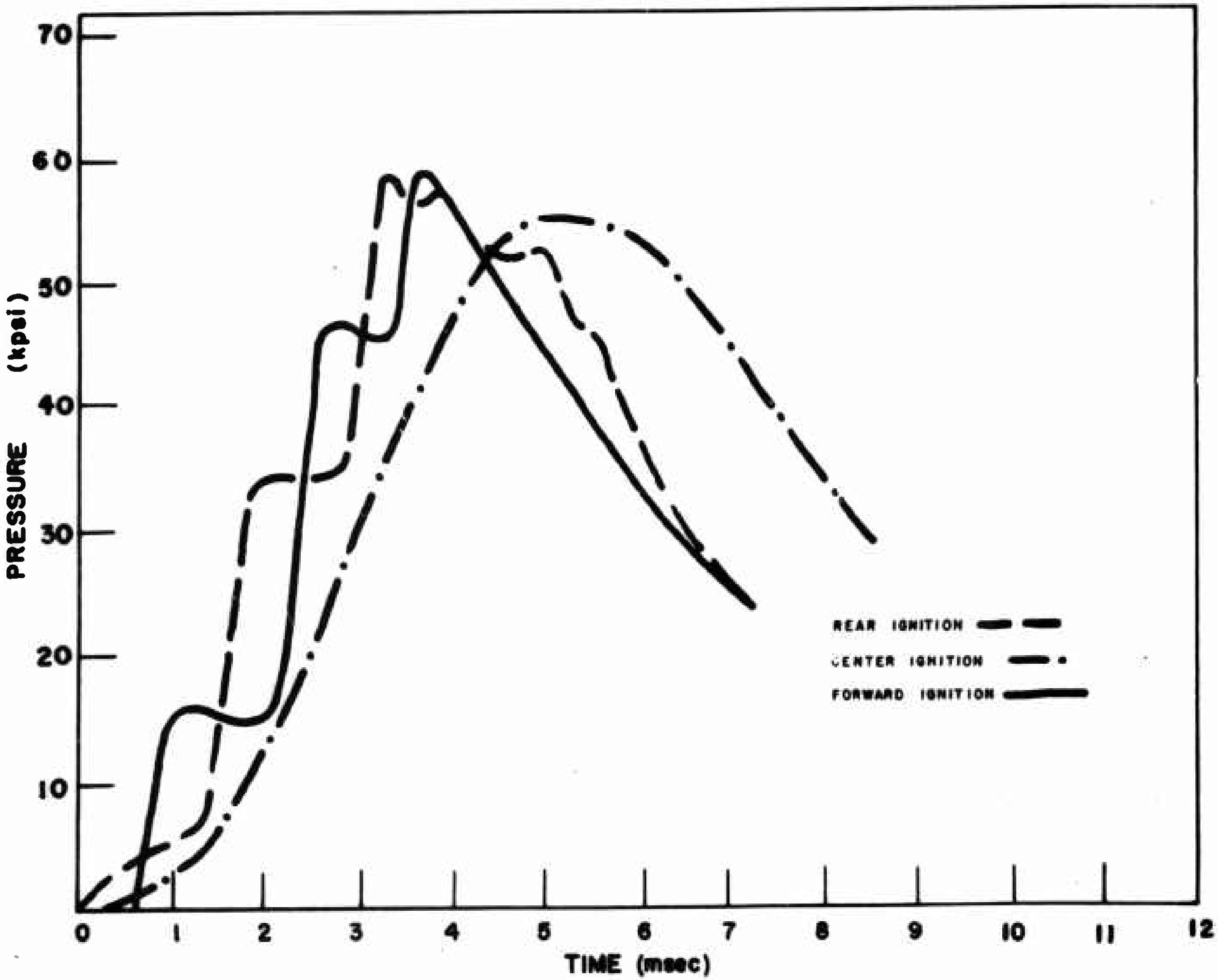


FIGURE 6. EFFECT OF POINT OF IGNITION UPON PRESSURE HISTORY

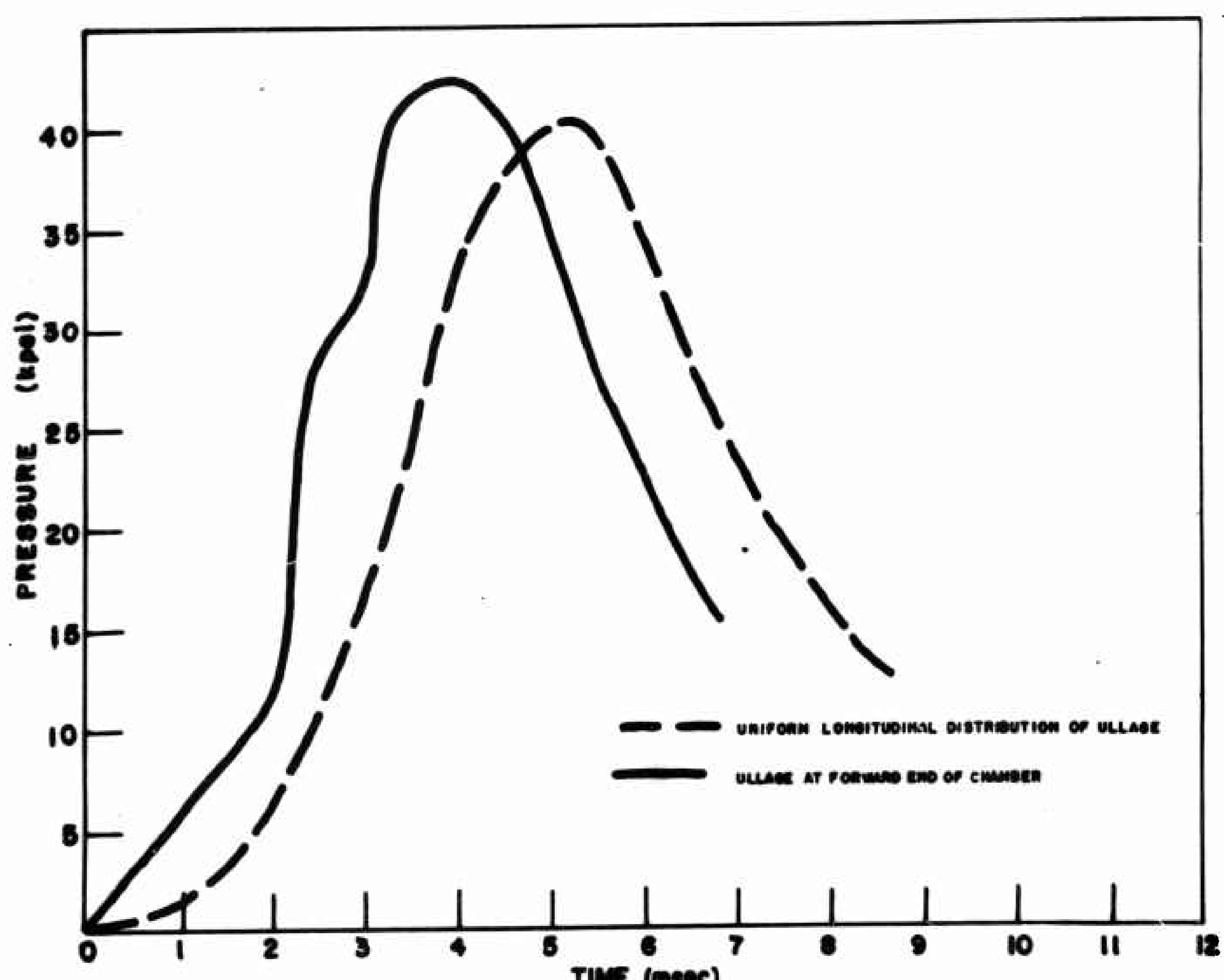


FIGURE 7. EFFECT OF CONFIGURATION OF THE ULLAGE ON THE PRESSURE HISTORY

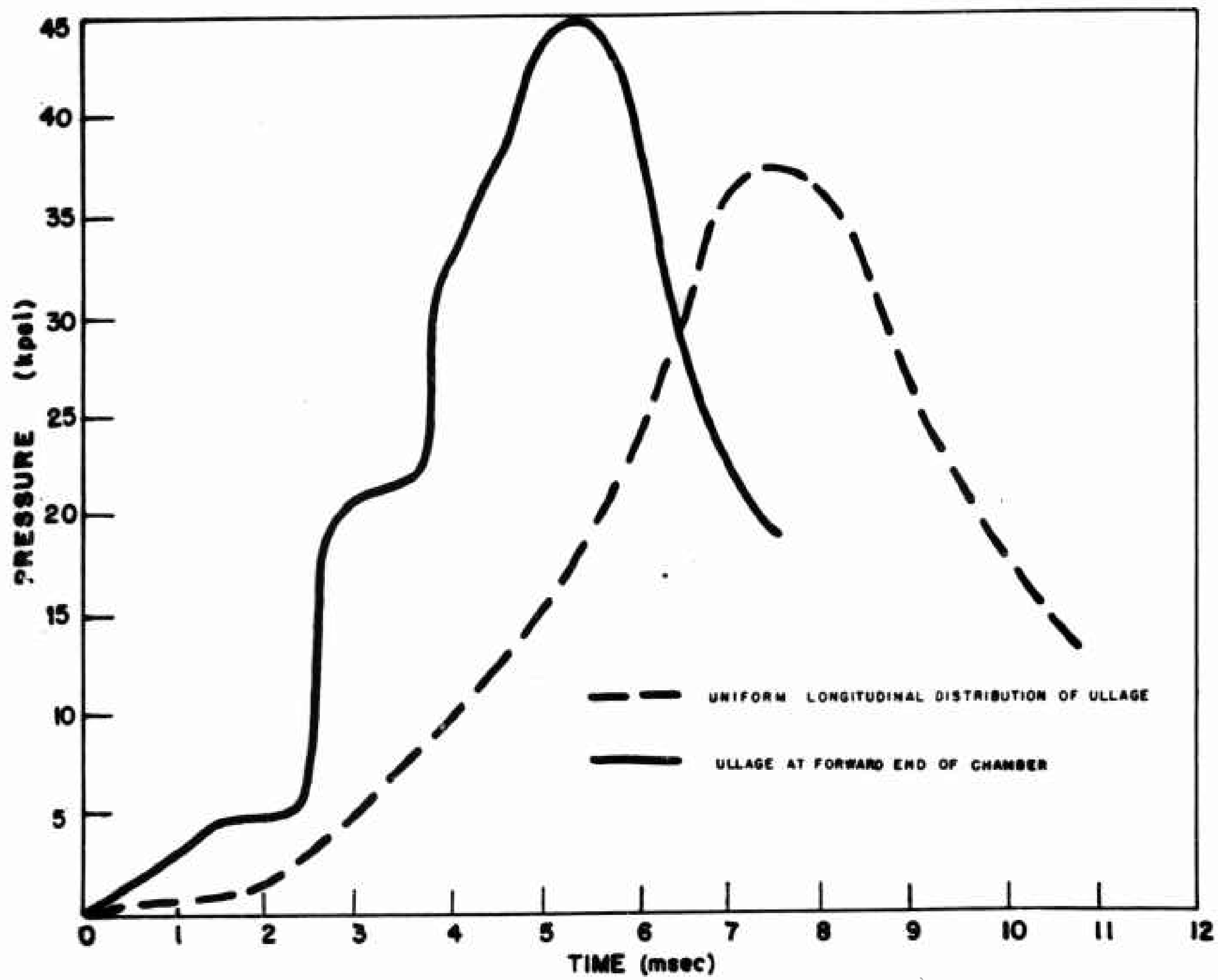


FIGURE 8. EFFECT OF CONFIGURATION OF THE ULLAGE ON THE PRESSURE HISTORY

3"/50 caliber gun are presented in Figure 8. This powder also produced pronounced pressure waves when poured in the conventional manner with a large void at the forward end of the case, but smooth pressure curves were obtained when the ullage was distributed longitudinally along one side of the case.

Having accumulated considerable evidence, similar in nature to the two preceding examples, that both the axial point at which the charge was ignited and the location and extent of the ullage were significant parameters in the origin and development of pressure waves, we next considered the possible interaction of these two factors in the formation of waves. It seemed reasonable to expect that the contribution of the ullage toward wave formation would tend to reinforce or neutralize the contribution of the ignition, depending on their relative spacial relations in the chamber. Combining this assumption with the fact that the initial rate of pressure rise could be expected to increase through the chamber both with increasing distance from the point of ignition and with the position of the ullage, a theoretical prediction of the space-time variations in pressure with varying spatial relations of the ignition and the ullage appeared feasible. However, the relative effectiveness of either ignition or ullage in determining the phase relations and amplitudes of the wave action which might develop in the chamber would be expected to vary with different chamber-igniter-propellant combinations.

This working hypothesis of the interaction of the point of ignition and location of the ullage in the formation of pressure waves predicts these general results: The largest amplitude pressure waves would result from rounds with the point of ignition adjacent to the ullage. The phase of the wave would be reversed by locating the point of ignition and ullage at the opposite end of the gun chamber. The wave amplitude would decrease as the point of ignition was moved away from the ullage toward the opposite end of the chamber with the lowest relative amplitude obtained with ignition and ullage at opposite ends of the chamber. Two ullages, one at either end of the chamber would neutralize each other, and the resulting wave would be the result primarily of the axial location of the point of ignition. Pressure waves would not develop in rounds with split ullages and with point of ignition at the center of the chamber.

By assigning relative effectivenesses in initiating wave action to the two parameters, we found we could, in most cases, predict, in a qualitative sense, the phase relations and amplitudes of the space-time variations in pressure for a given spatial relation of point of ignition and ullage. However, though agreement with empirical results were good, in many cases the empirical results were from firings in which possible contributions from other parameters could not be eliminated.

To test the validity of our working hypothesis of the interaction of point of ignition and position of the ullage in the formation of pressure waves under controlled conditions, we carried out a firing program in the 5"/38 blow-out gun. This program consisted of a block of nine rounds which comprised all combinations of rear, center and forward ignition with rear, forward and split ullages. The primers used in these firings were designed especially for these tests in an attempt to obtain, insofar as practical, a uniform type of ignition at the different positions in the charge. The booster charge (300 grains of black cannon powder) was loaded in the vented section of standard primer tubes and maintained in this position, by spacers forward and aft of the vented section, until ignited. The vented section comprised 12 holes arranged in four rows, with the holes spaced one inch apart in the rows and the holes staggered in adjacent rows. This arrangement of the holes restricted the vented section to about 2.5 inches in the axial direction. The volumes within the primer tubes available to the primer gases were the same for each group of three primers used with each ullage arrangement, but differed slightly for the three different ullage configurations.

The sets of pressure-time curves obtained in the firing of the nine test rounds are presented in Figures 9 through 17. In addition to the pressure curves obtained at 3, 14 and 25 inches in the blow-out gun chamber, a schematic diagram is included in each figure which shows the spatial relations of the propellant, igniter, ullage, pressure gauges and orifice in the chamber.

Approximations to the pressure-space relations existing in the chamber during the first 5 to 6 milliseconds of the pressure cycle for the nine rounds are presented in Figures 9A through 17A. These curves are the results of

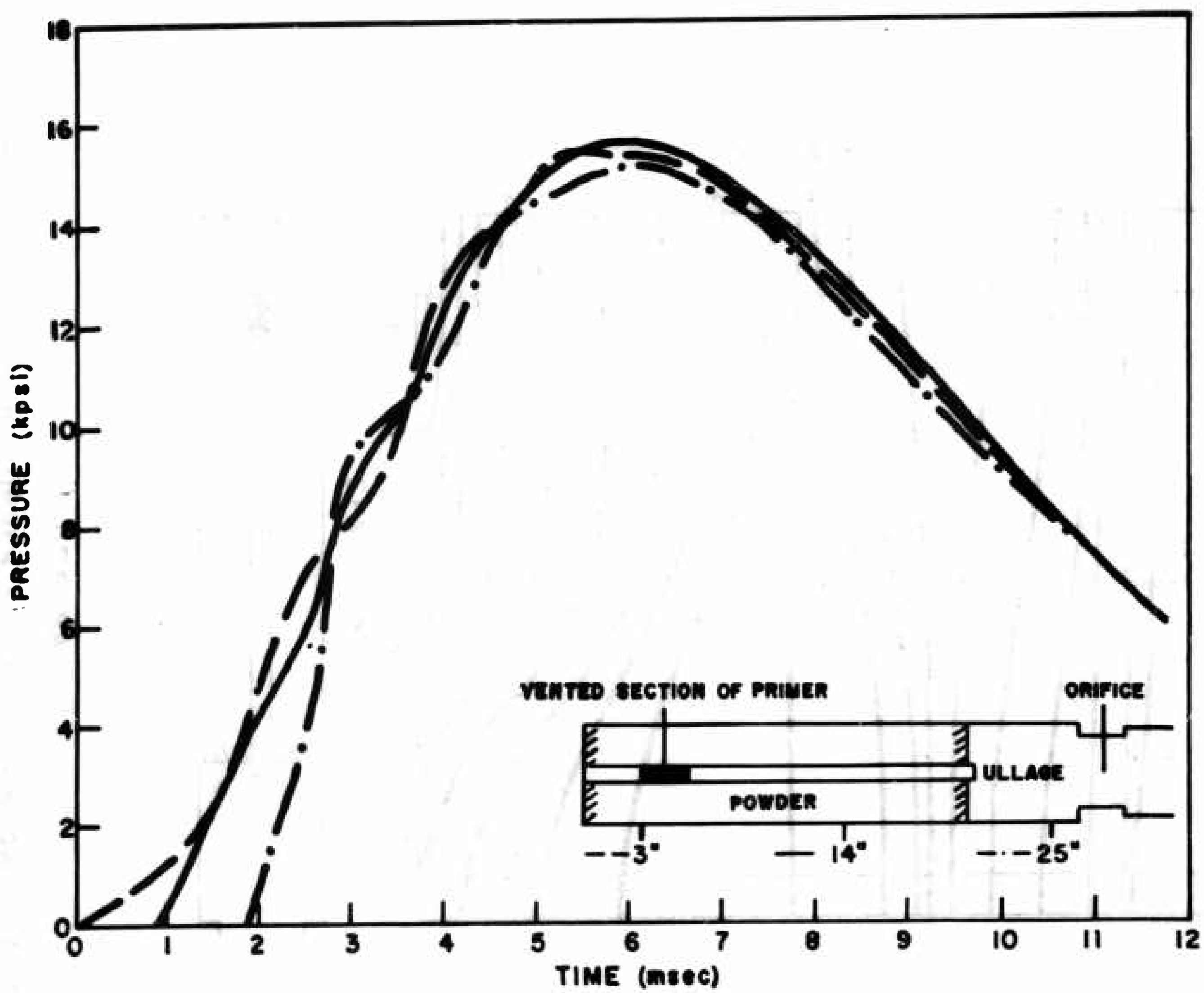


FIGURE 9. PRESSURE-TIME CURVES FROM 5"/38 BLOW-OUT GUN

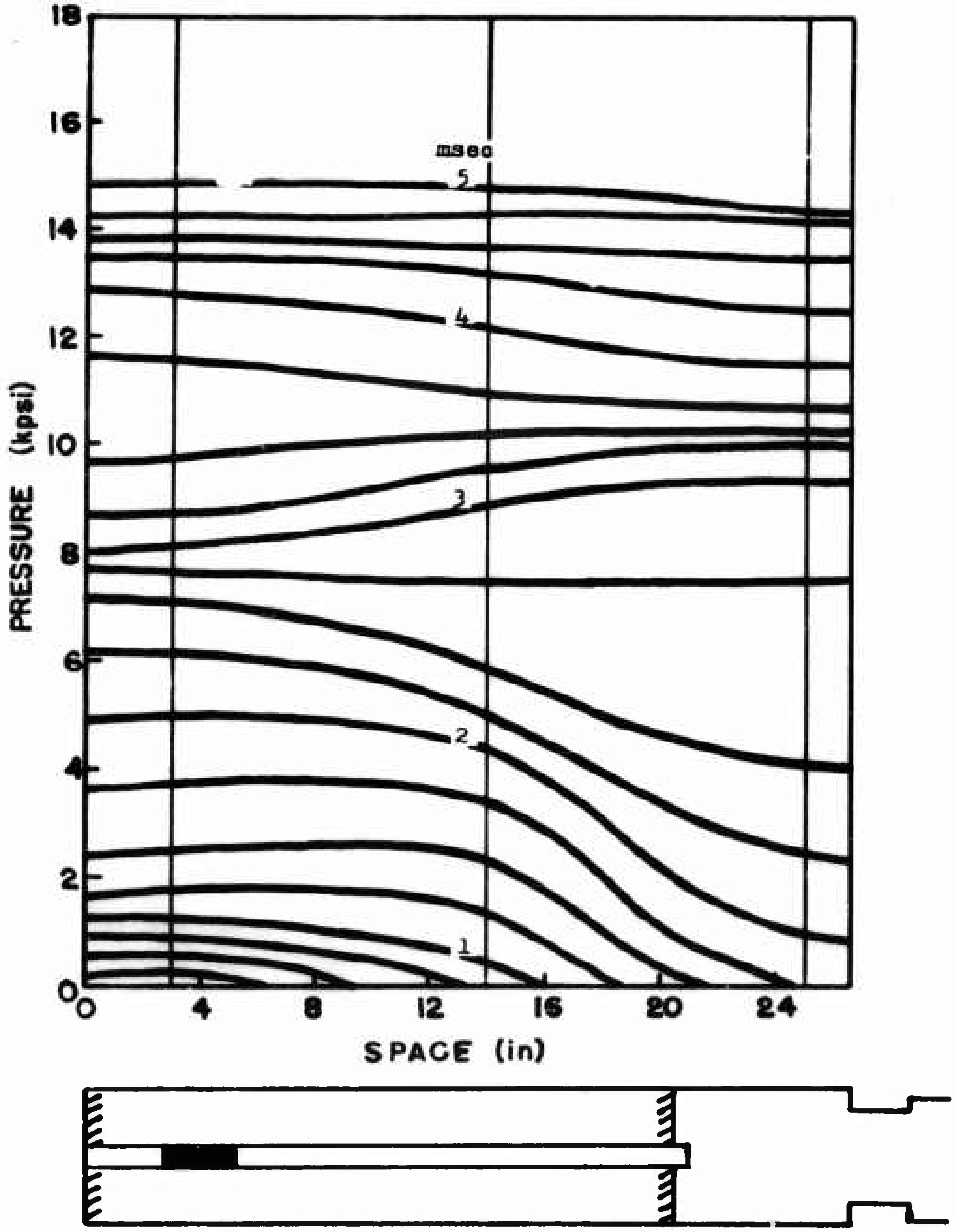


FIGURE 9A

PRESSURE-SPACE CURVES FROM 5"/38 BLOW-OUT GUN

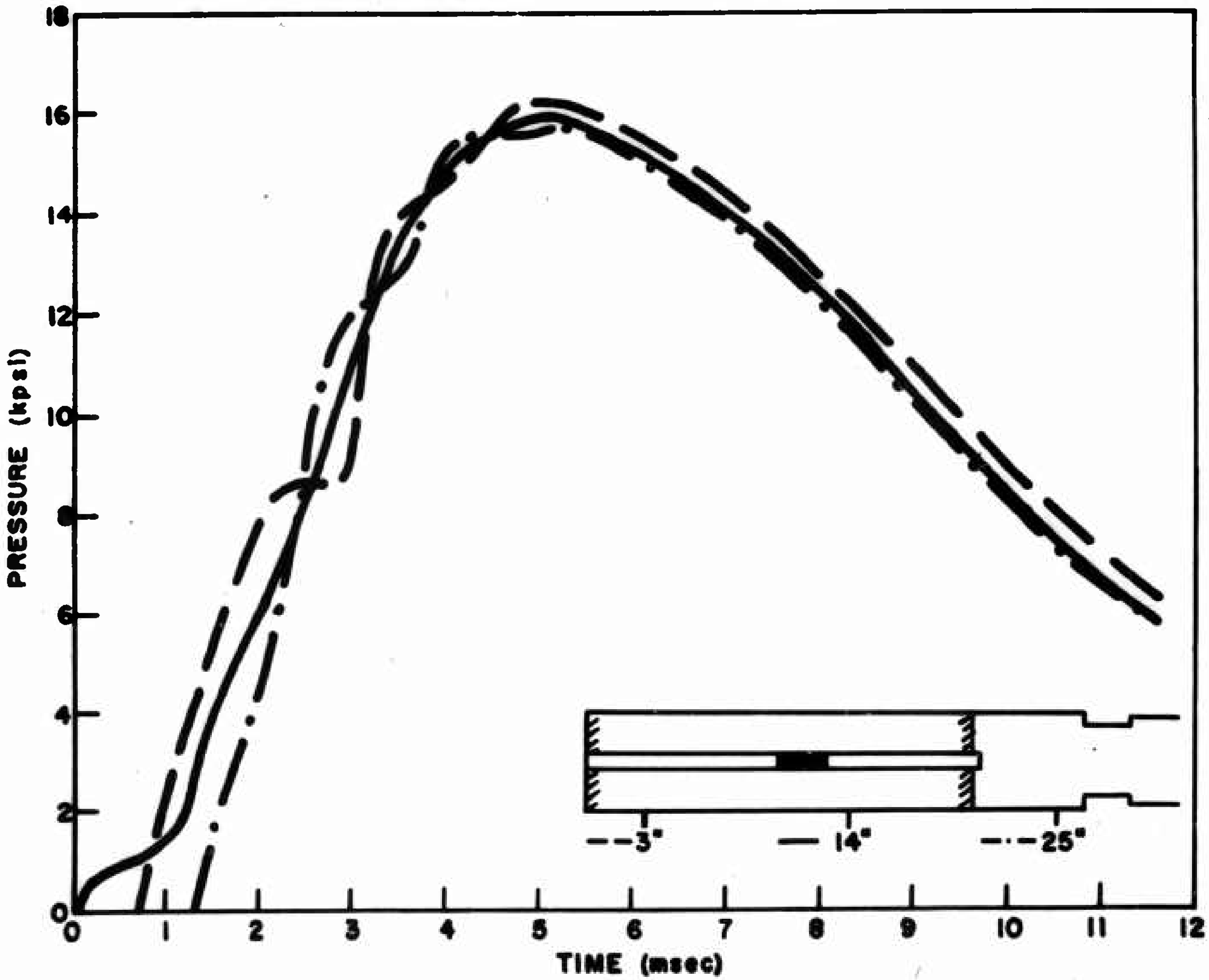


FIGURE 10. PRESSURE-TIME CURVES FROM 5"/38 BLOW-OUT GUN

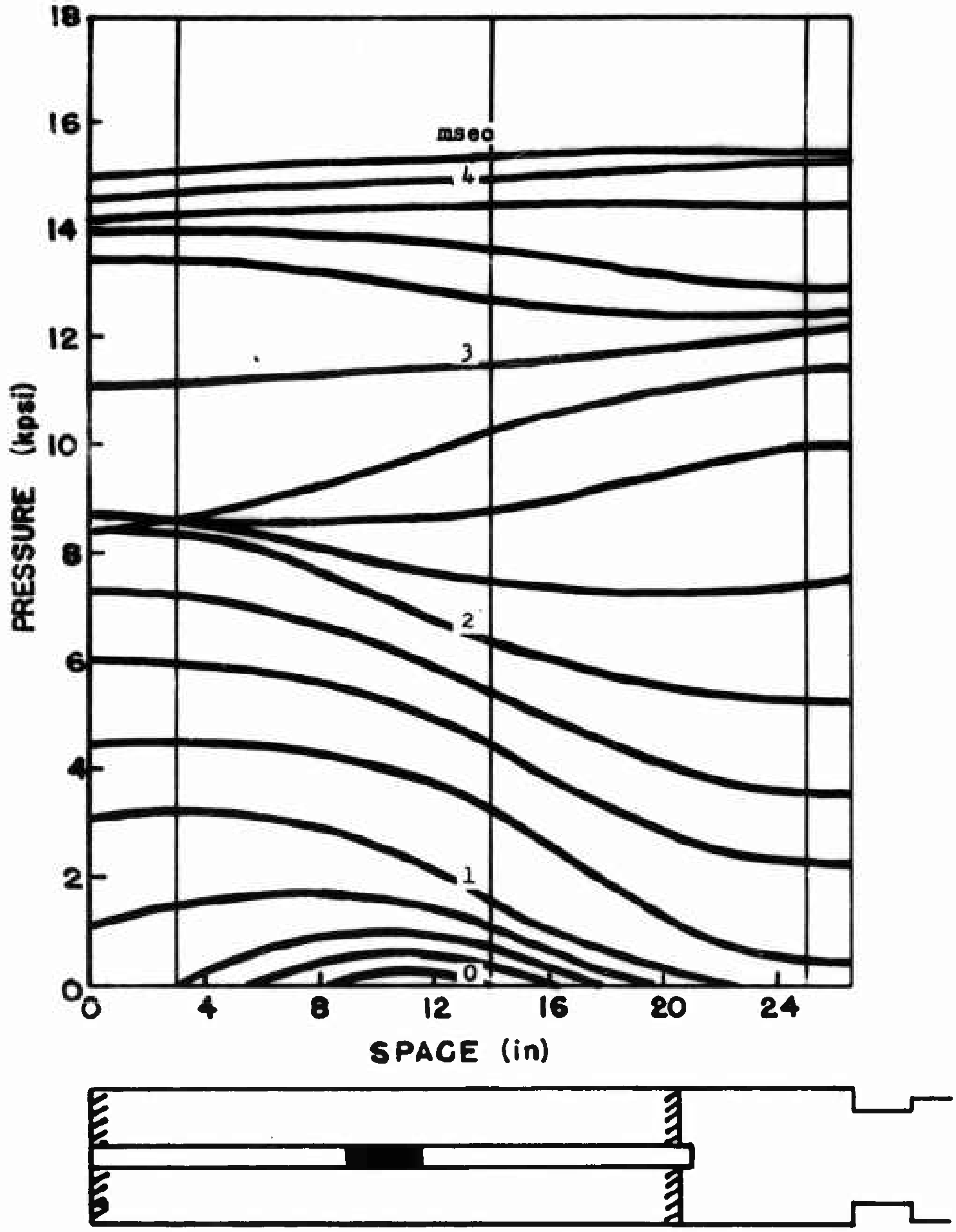


FIGURE 10A

PRESSURE-SPACE CURVES FROM 5"/38 BLOW-OUT GUN

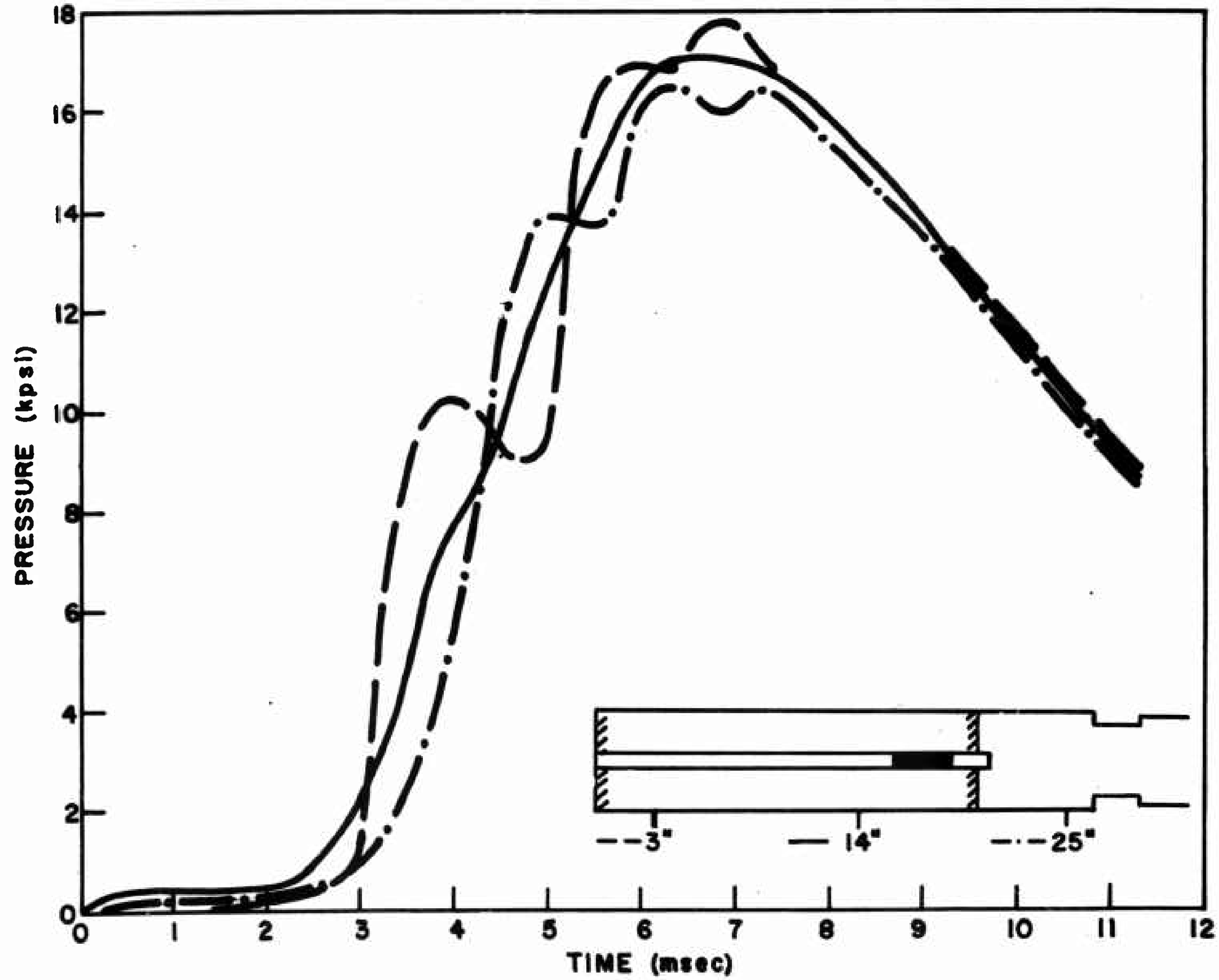


FIGURE 11. PRESSURE-TIME CURVES FROM 5"/38 BLOW-OUT GUN

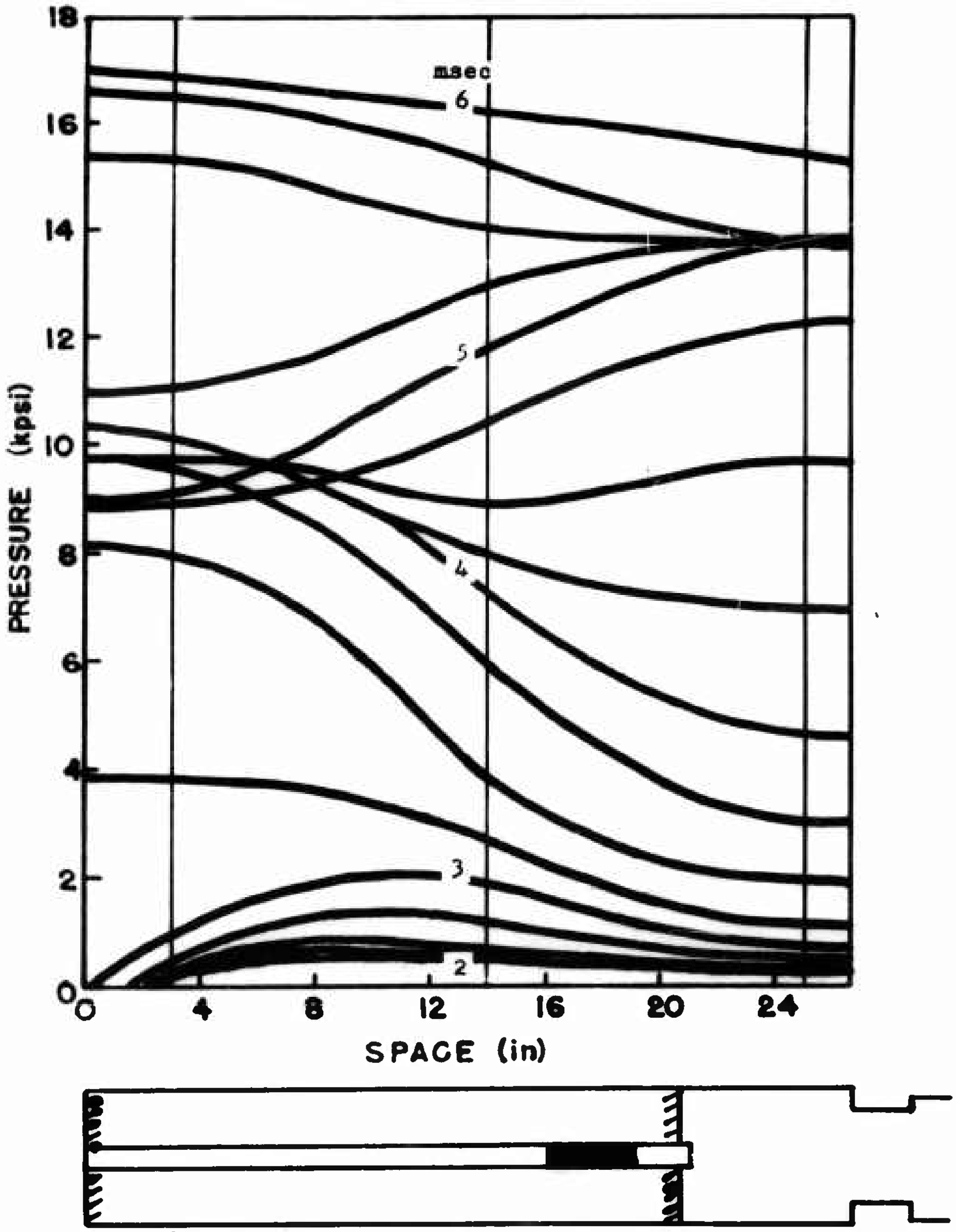


FIGURE 11A

PRESSURE-SPACE CURVES FROM 5"/38 BLOW-OUT GUN

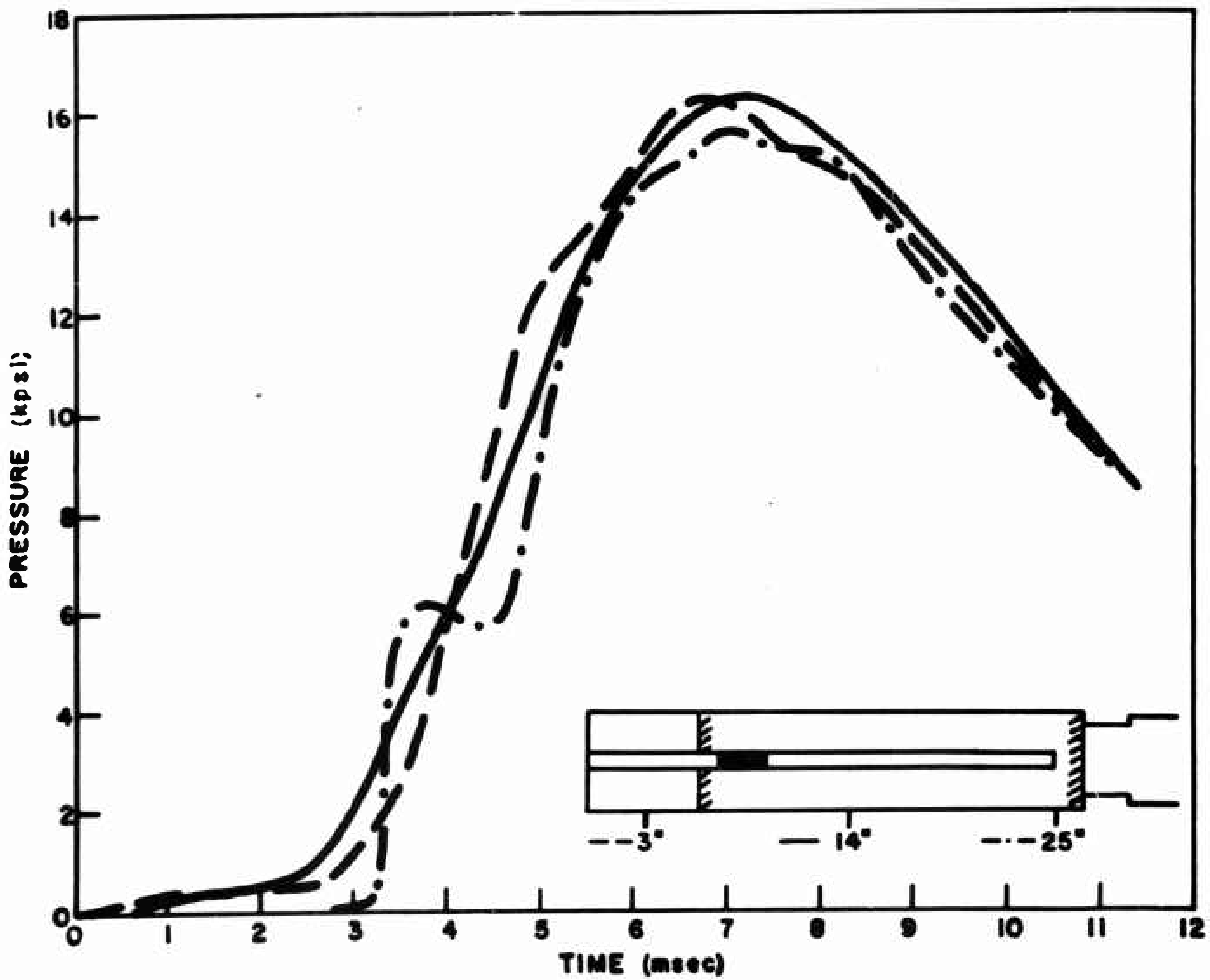


FIGURE 12. PRESSURE-TIME CURVES FROM 5"/38 BLOW-OUT GUN

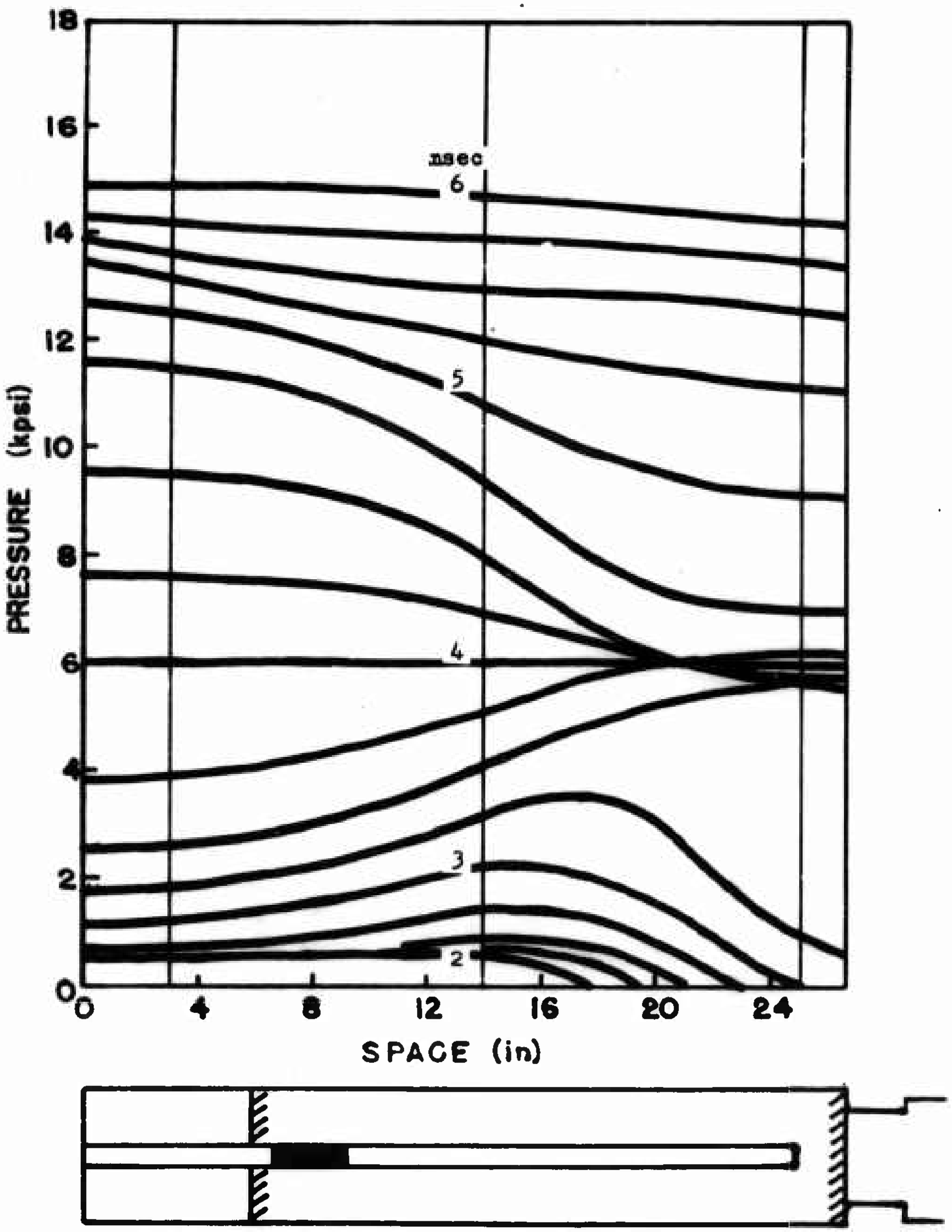


FIGURE 12A

PRESSURE-SPACE CURVES FROM 5"/38 BLOW-OUT GUN

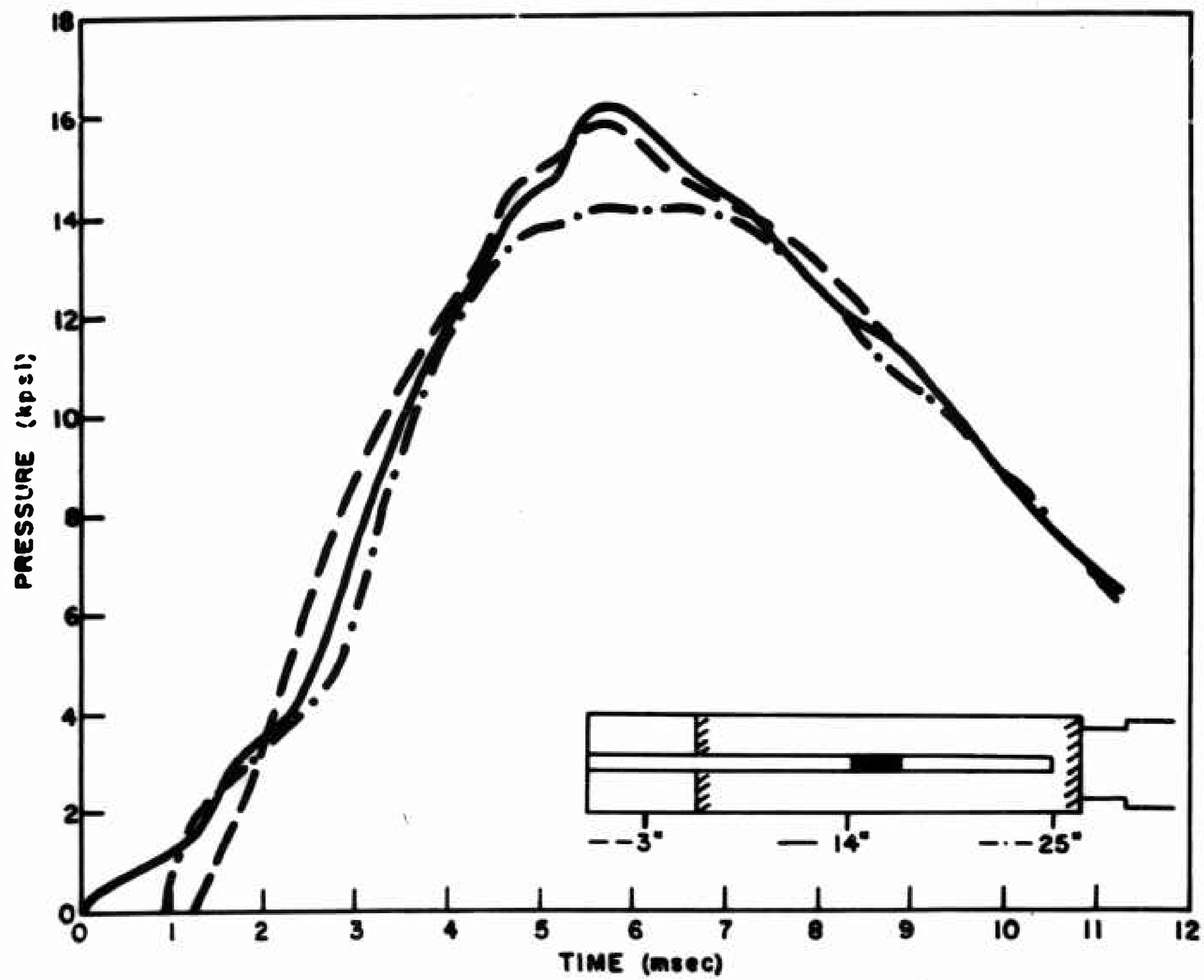


FIGURE 13. PRESSURE-TIME CURVES FROM 5"/38 BLOW-OUT GUN

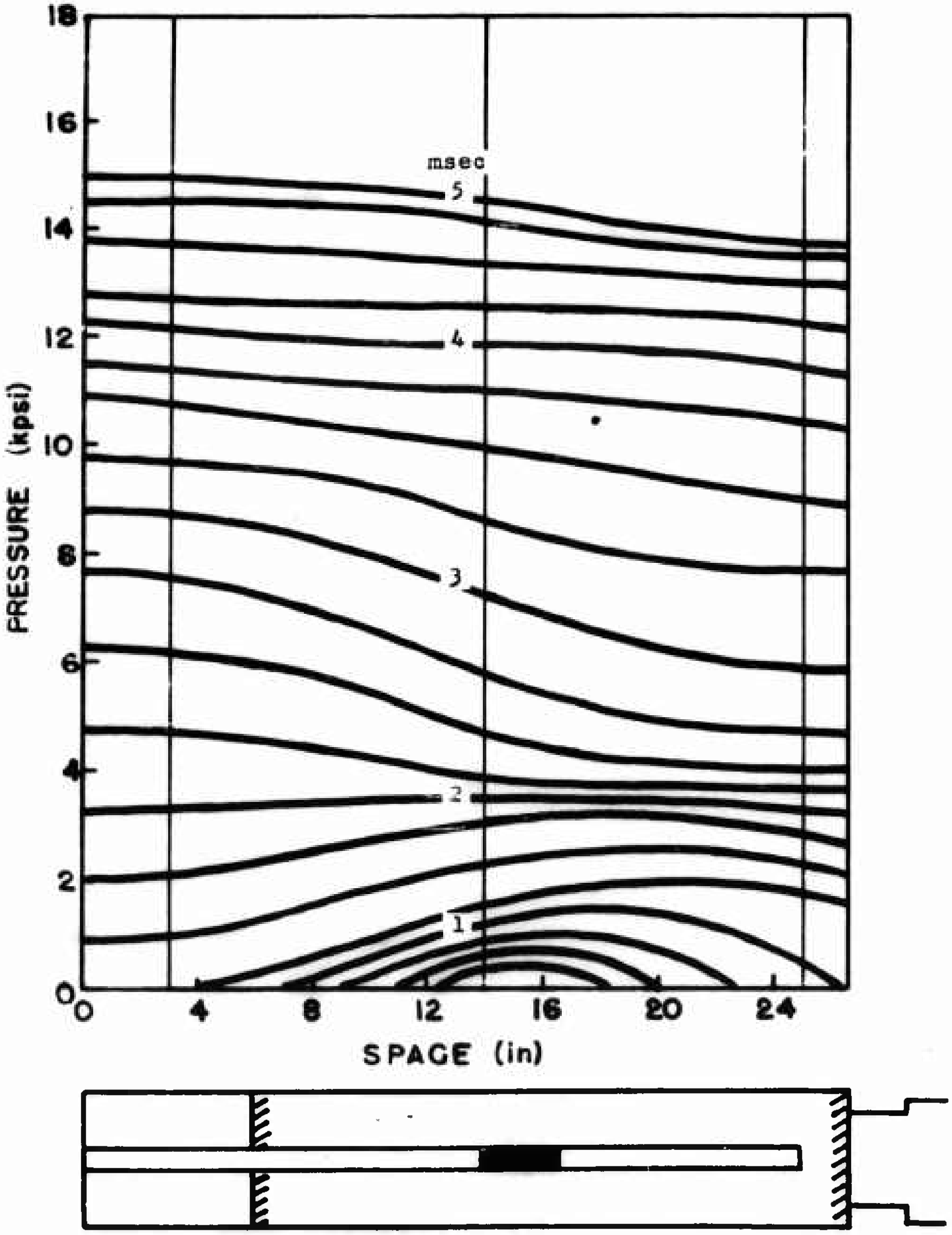


FIGURE 13A

PRESSURE-SPACE CURVES FROM 5"/38 BLOW-OUT GUN

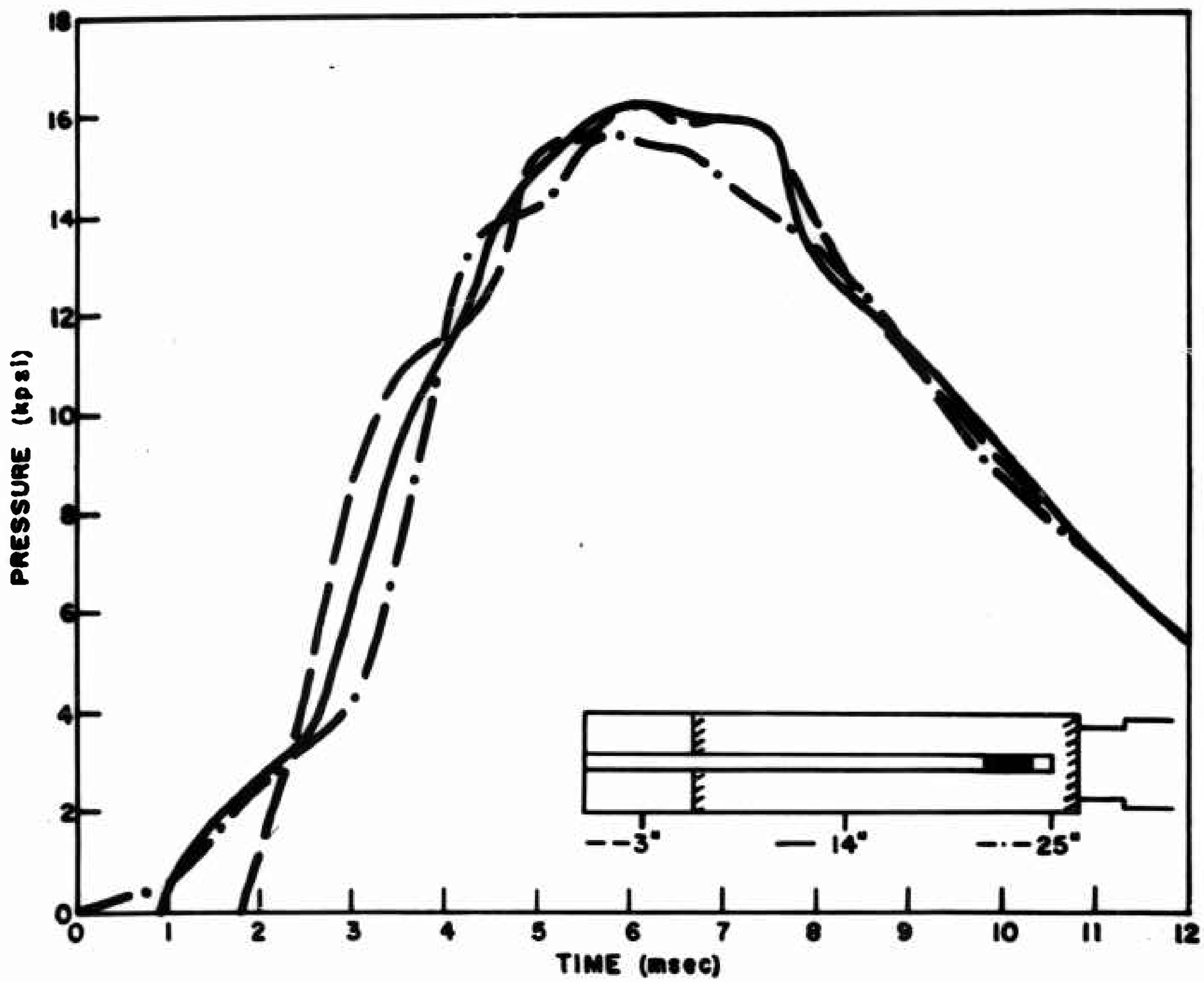


FIGURE 14. PRESSURE-TIME CURVES FROM 5"/38 BLOW-OUT GUN

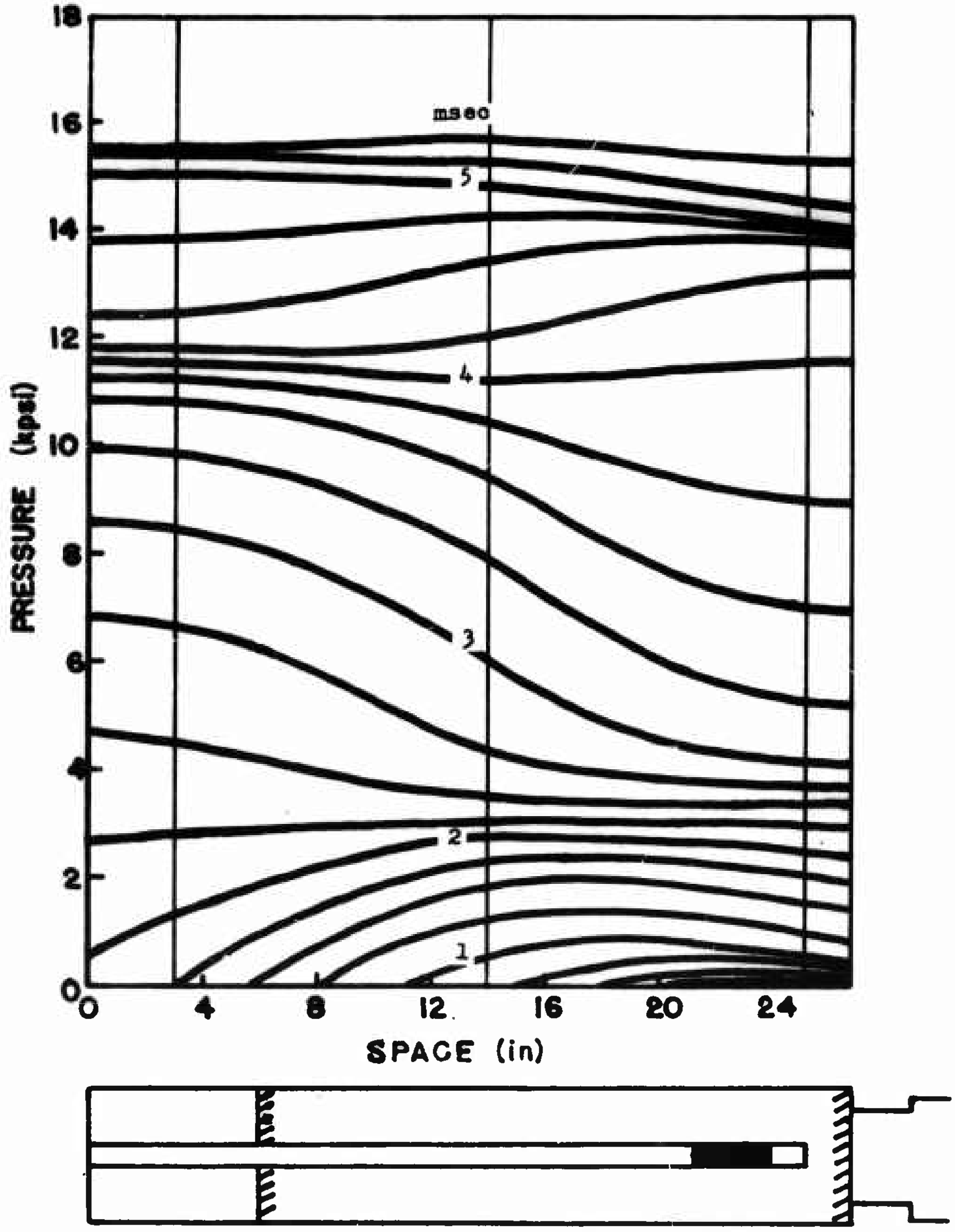


FIGURE 14A

PRESSURE-SPACE CURVES FROM 5"/38 BLOW-OUT GUN

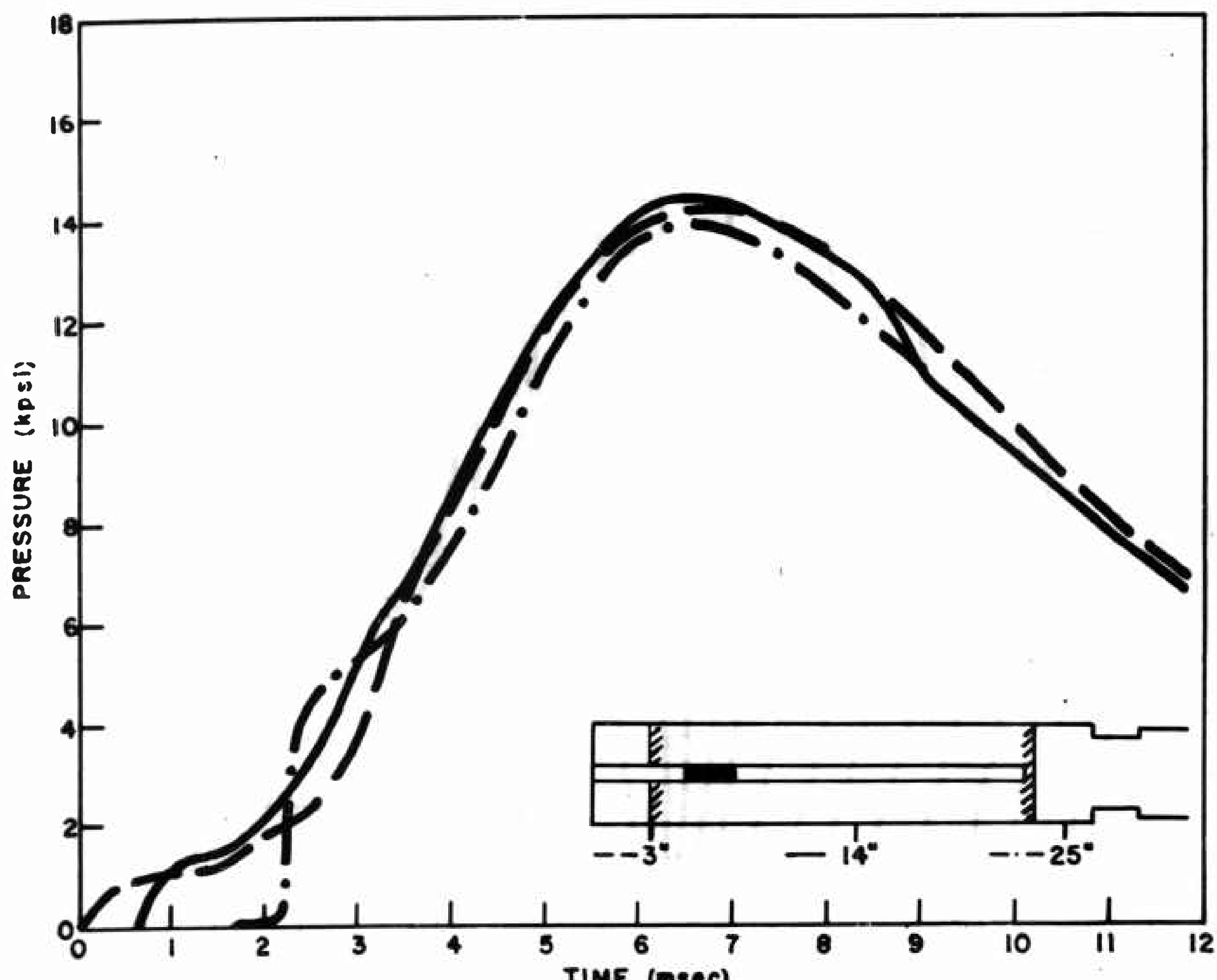


FIGURE 15. PRESSURE-TIME CURVES FROM 5"/38 BLOW-OUT GUN

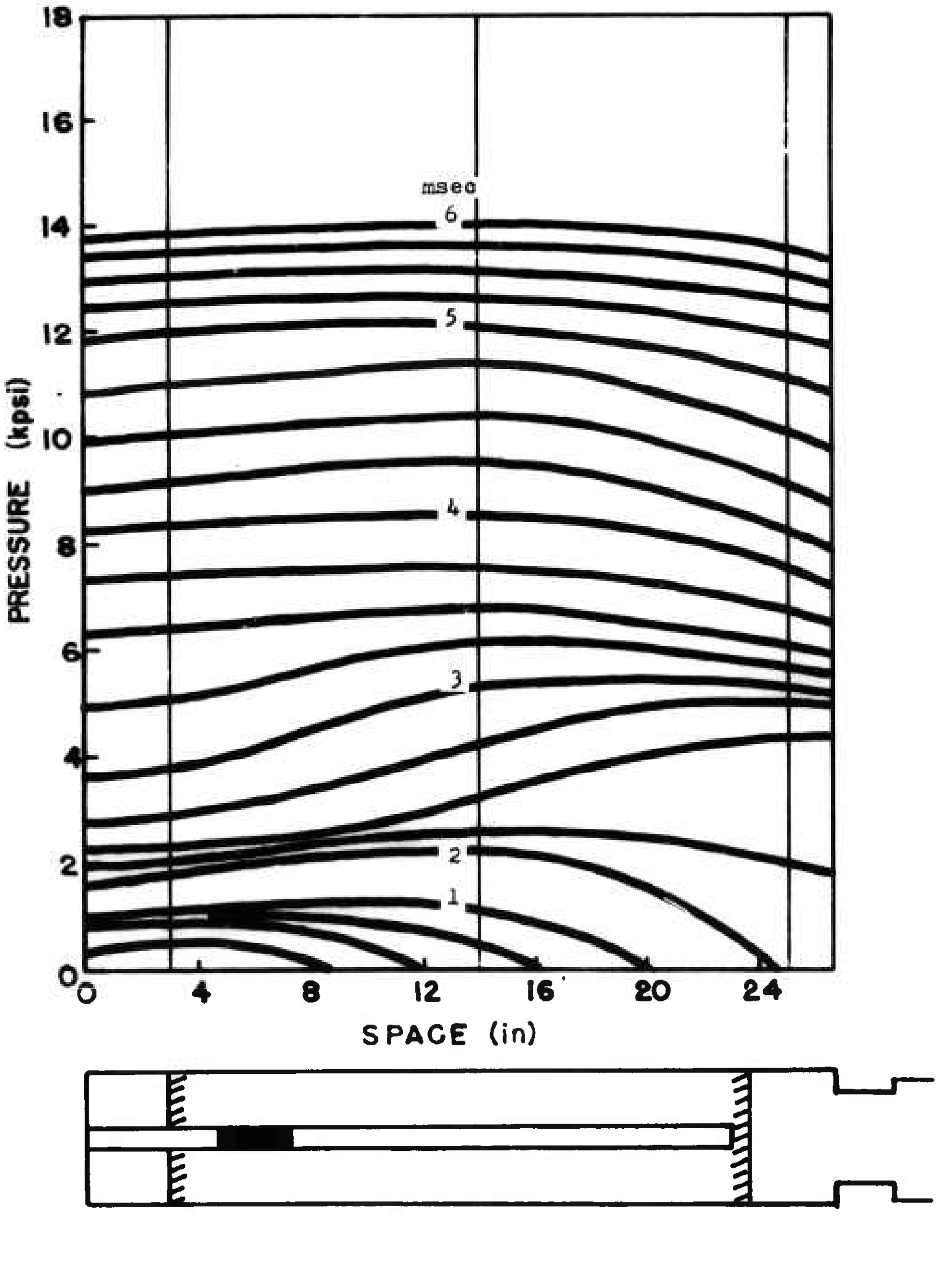


FIGURE 15A

PRESSURE-SPACE CURVES FROM 5"/38 BLOW-OUT GUN

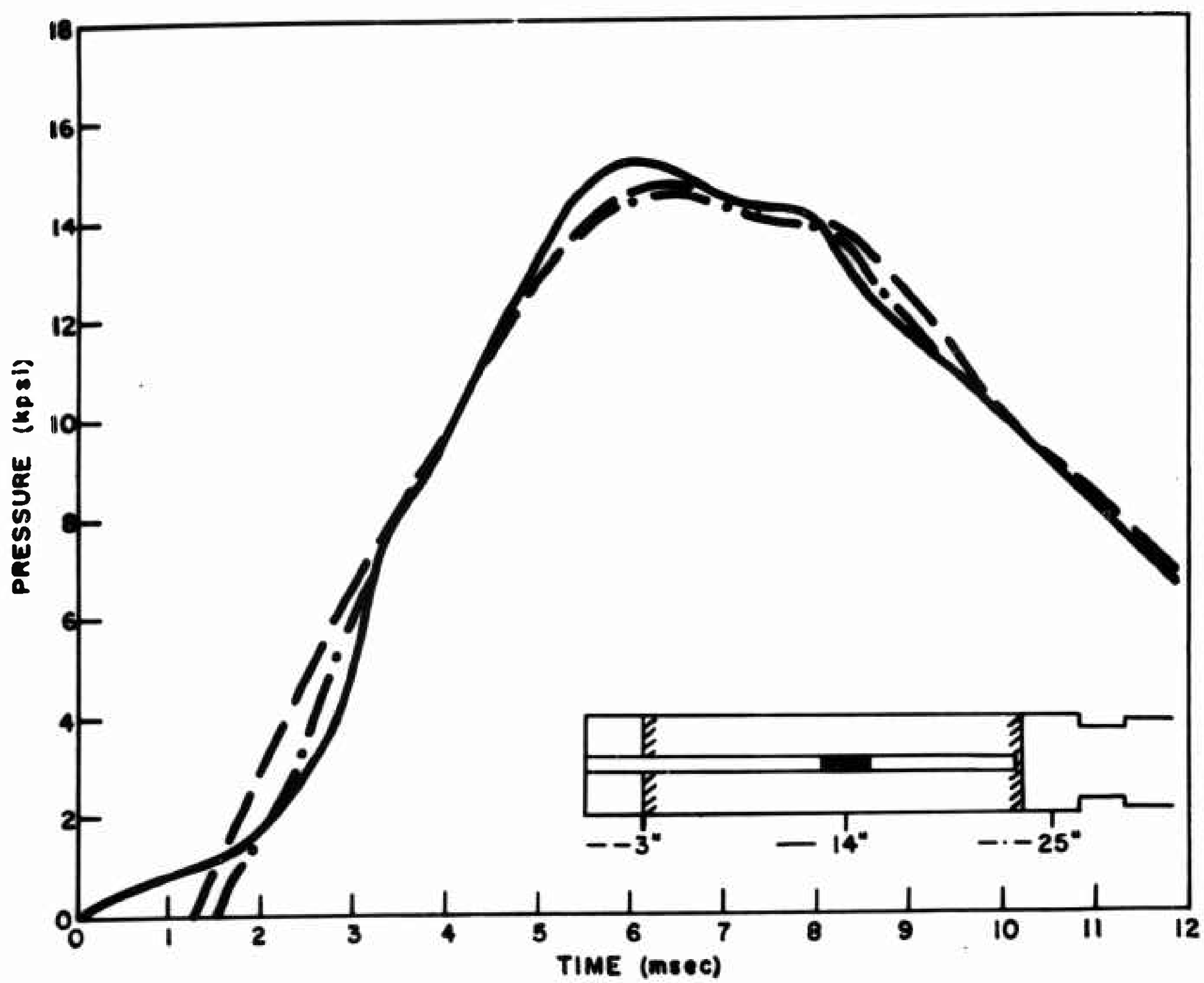


FIGURE 16. PRESSURE-TIME CURVES FROM 5"/38 BLOW-OUT GUN

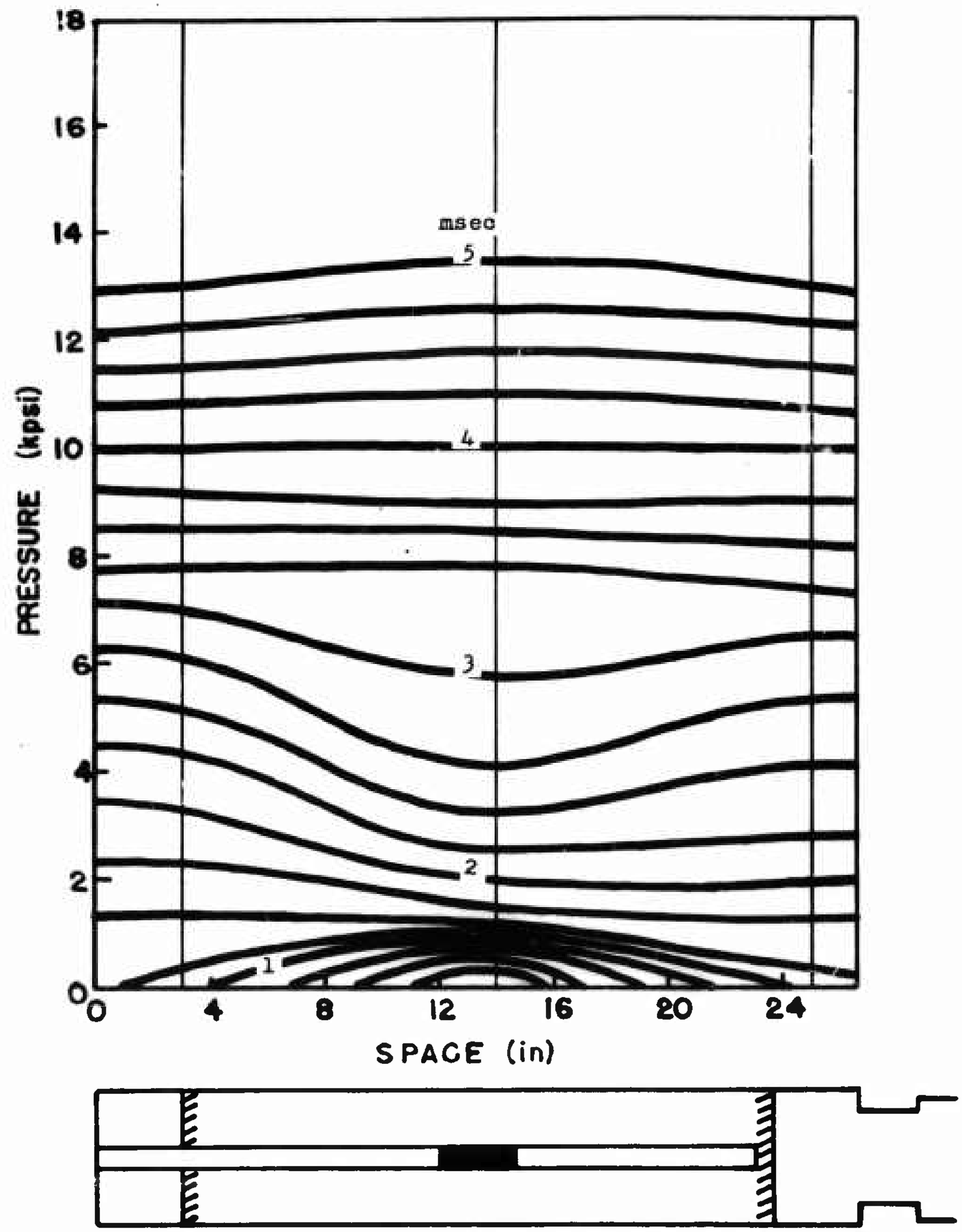


FIGURE 16A

PRESSURE-SPACE CURVES FROM 5"/38 BLOW-OUT GUN

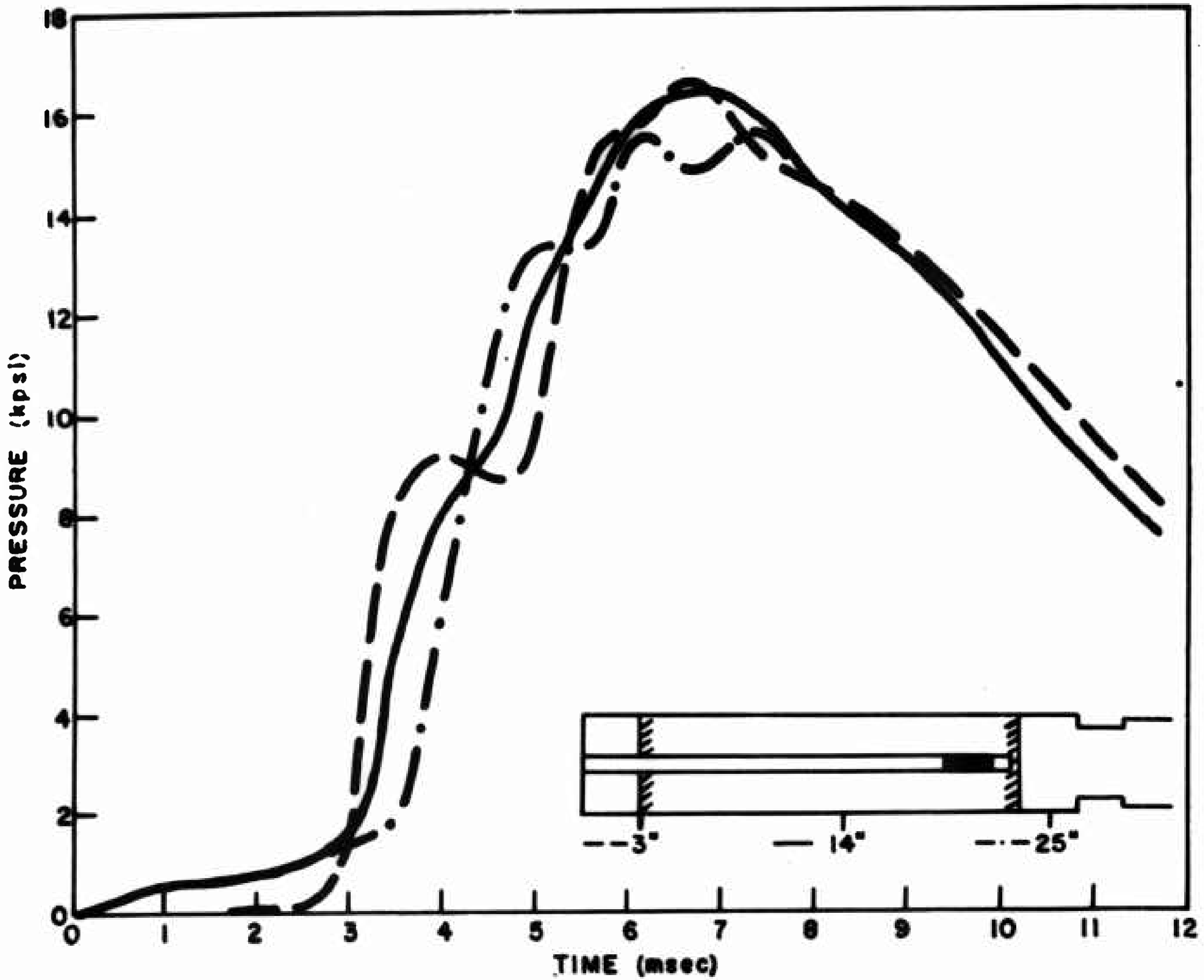


FIGURE 17. PRESSURE-TIME CURVES FROM 5"/38 BLOW-OUT GUN

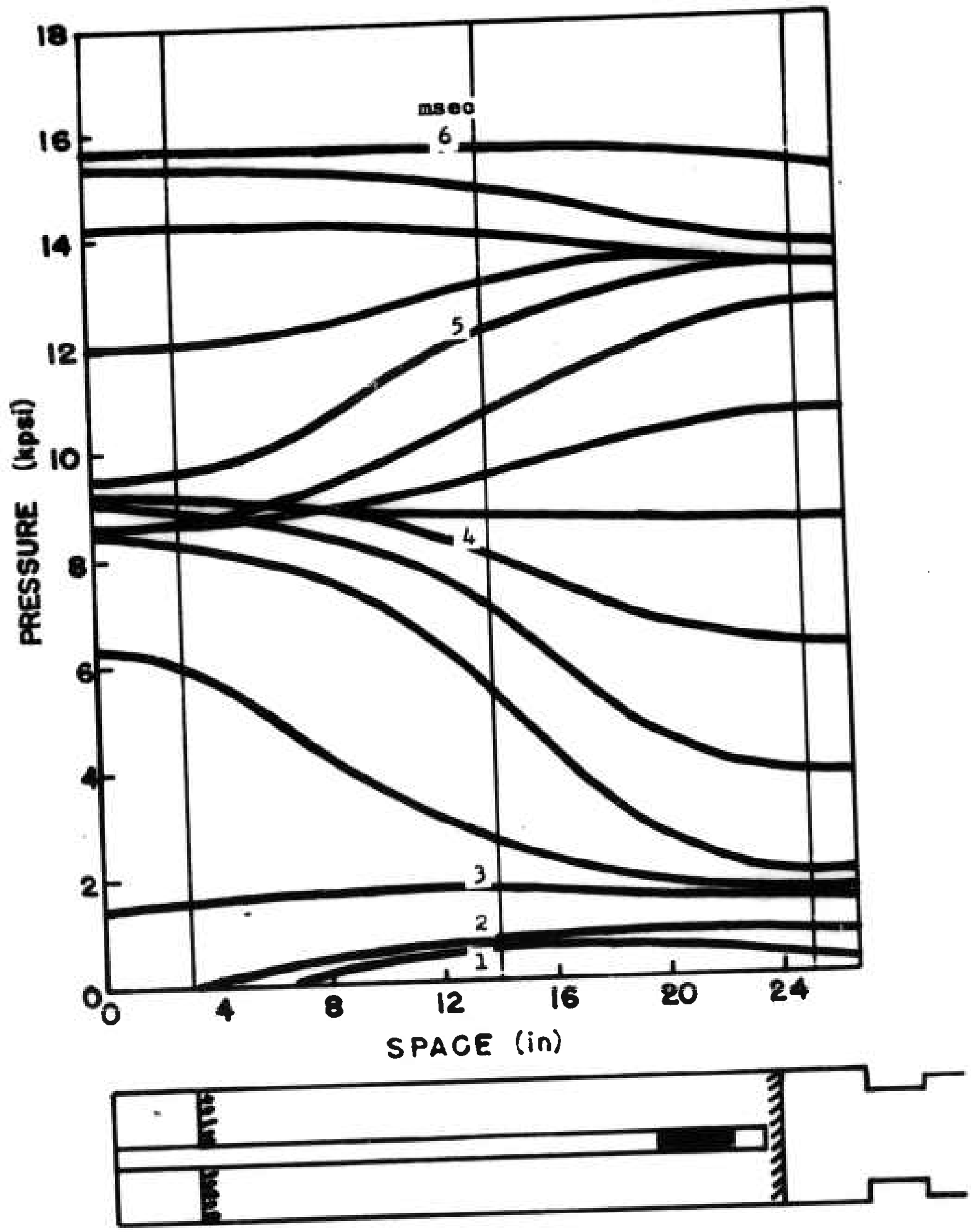


FIGURE 17A

PRESSURE-SPACE CURVES FROM 5"/38 BLOW-OUT GUN

plotting the pressures at the three gauge stations at one-quarter millisecond intervals on pressure-space coordinates and drawing approximations to cosine curves through the isochronic pressure points. The cosine pressure-space relations follow from the standing wave character of the pressure waves and were confirmed also by pressure recordings at stations intermediate between the center and end gauge stations. These sets of curves are believed to be sufficiently close approximations to the pressure gradients actually existing in the gun chamber to provide an overall picture of the pressure-space variations in the chamber and to be useful in demonstrating the manner in which pressure gradients in the chamber develop into standing waves.

In the particular charge-igniter-ullage combinations of these rounds, the point of ignition appeared to dominate somewhat the location of the ullage in determining both the phasing and amplitude of the waves formed. The ullages located at the rear of the chamber appeared somewhat less effective in forming waves than did the forward ullages. This is probably to be explained as a result of two factors. The forward ullages were maintained simply by gluing a pyralin wad to the case wall immediately ahead of the charge, while the rear ullages were formed by inserting conventional cardboard spacers and wads in the base of the case before pouring the charge. This latter arrangement no doubt offered greater resistance to the passage of gases and propellant grains into the free space and also reduced somewhat the effective volumes of the ullages. On the other hand, the orifice adjacent to the forward ullages probably tended t increase somewhat the apparent effective volumes of these ullages.

In the first three rounds (Figures 9, 10 and 11) the powder was poured in the conventional manner with the ullage forward of the powder. With ignition in the rear section of the charge (Figure 9) a relatively small amplitude wave developed. The wave amplitude increased somewhat with center ignition (Figure 10) and became comparatively large with ignition at the forward end of the charge (Figure 11). The arrangement of ignition adjacent to the ullage in the last case is a condition for large amplitude waves, the effect of the ignition being reinforced by that of the ullage. In Figure 9, on the other hand, a low amplitude wave results from the effect of the ullage tending to neutralise that of the ignition. Figure 10 is an intermediate condition; in the absence of the ullage smooth pressure-time relations would be anticipated with center ignition.

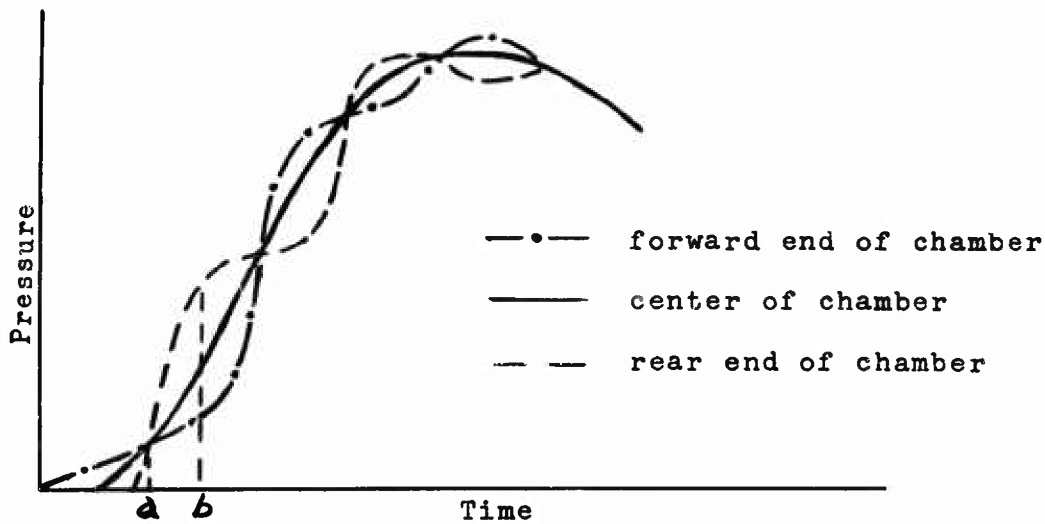
In the next set of three rounds (Figures 12, 13 and 14) the ullage was located at the after end of the chamber. The juxtaposition of ullage and ignition in Figure 12 is again a condition for pronounced wave development, and this is the result obtained. The wave pattern from this round is somewhat obscured in the higher pressure levels by the pressure gradient decreasing toward the forward end of the chamber which developed in this phase of the pressure cycle. It is to be noted that the phasing of the wave in this case is the reverse of that obtained in the preceding round with ignition and ullage at the forward end of the chamber. Moving the ignition to the center of the charge in Figure 13 reduces the wave amplitude, while moving the ignition to the forward end of the chamber (Figure 14) tends to increase the amplitude somewhat over that obtained with the center ignited round. These results indicate a reduced effectiveness of the rear ullages as compared to those forward of the charge. Were these ullages of comparable effectiveness to those forward of the charge, a somewhat greater amplitude wave could be expected in Figure 13 and a wave of lower amplitude in Figure 14.

In the last set of three rounds (Figures 15, 16 and 17) the ullage was divided, half being located at each end of the chamber. In this set the two ullages can be expected to neutralise each other and the wave action will be that primarily due to the point of ignition. With the rear ignition in Figure 15 the phasing of the wave is the same as that of Figure 12, but the amplitude is less, as would be anticipated from the reduced ullage adjacent the igniter. In Figure 16 we have the condition for minimum wave development, center ignition and ullage divided equally at the two ends of the charge. The center ignition tends to produce higher initial rates of pressure rise at the two ends of the chamber, resulting in the momentary lower pressure at the center of the chamber. But upon reflection these higher end pressures, because of their symmetrical spacing in the chamber, raise the pressure at the center and establish a uniform pressure throughout the chamber. With the forward ignition in Figure 17 a pronounced wave again develops. Here again the rear ullage appears to be less effective than the forward ullage plus the adjacent orifice, and the amplitude of the wave is somewhat greater than would be expected from equally effective ullages at the two ends of the chamber.

These experimental results substantiate, in all essential aspects, our preliminary working hypothesis of the interaction of point of ignition and ullage in the formation of pressure waves. The hypothesis thus appears to be a useful rule-of-thumb method of predicting the results to be expected from different spatial arrangements of the igniter and ullage in the charge make-up.

Further analysis of the space-time variations in pressure occurring in the above and related firings leads to the conclusion that pressure waves develop in gun chambers as a result of pressure gradients set up in the chamber in the initial stages of the pressure cycle in combination with motion and differential packing of the propellant resulting from the initial gradients. Hence, any parameter which contributes to an initial pressure gradient in the gun chamber becomes a potential source of pressure waves. However, the effect of one parameter may be neutralized by a second which tends to create a gradient in the opposite direction, and conversely the tendency for a wave to develop may be increased by two or more parameters tending to establish a gradient in one direction in the chamber. Motion and differential packing of the powder appears to be of particular significance in determining the amplitude of the pressure wave which eventually develops.

Let us consider this theory in relation to a specific case - that of a round with both ignition and ullage at the forward end of the chamber. The pressure-time-space curves for such a round are presented in Figures 11 and 11A and ideally will be found to be approximately as diagramed as follows:



During the time of passage of the ignition front (considered as the interval between first indications of pressure at the forward and rear ends of the chamber in this case) there exists a pressure gradient decreasing toward the rear of the chamber. It is postulated that under the influence of this gradient, combined with the effects from the forward ignition, powder tends to pack toward the rear of the chamber. The resulting increase in loading density rearward, coupled with the resistance to flow of gases offered by the powder bed, results in a rate of pressure rise at the rear of the chamber greater than that in the center of the chamber. On the other hand, the rearward motion of the powder reduces the density of loading at the forward end of the chamber, tending to result in a lower rate of burning at this end. The ullage and orifice contribute to this reduced rate of rise in pressure by making available additional volume into which the gases in this section of the chamber can expand.

The differential rate of pressure rise through the chamber overcomes the initial pressure gradient and in turn produces a gradient in the opposite direction. This carries the pressure cycle beyond point a in the above sketch. The reversed gradient accelerates the powder grains now toward the forward end of the chamber, and reduces the amount of powder in the rear of the chamber. As a consequence, the rate of pressure rise decreases in this end of the chamber. The gas flow is also toward the forward end of the chamber during this phase and contributes to the lowered rate of pressure rise. Concurrently, the grains begin to pack in the forward section of the chamber. The rate of pressure rise increases at this end due to the increased burning rate and influx of powder gases and becomes greater than the decreasing rate at the rear of the chamber. As the rates of pressure rise at the two ends become equal (at point b in the sketch) the first quarter cycle of the pressure wave is completed. The pressure gradient has developed into a standing wave. This quarter cycle of the wave appears to be critical in that the amplitude of the wave is largely (though not completely) determined in this interval.

Left to itself, the wave could be expected to continue in the chamber by reflections at the two ends until damped out. However, since a large fraction of the charge is yet unburned at this stage, further concentrations of the grains are possible under the influence of the pressure gradients in the wave. These concentrations of grains combined with the dependence of the burning rate on pressure, are conceived to operate in a regenerative or feed-back manner to maintain, or even increase, the wave amplitude in later segments of the wave. In fact, it is a frequent occurrence for the amplitude of the pressure wave in its second half cycle to equal or exceed that attained in the first half cycle.

By this view of wave formation the role of the ullage is primarily that of augmenting the burning front gradient set up by the igniter. While its effect in this may be considerable, the absence of an ullage would not prevent a gradient being established.

An analysis similar to the above can be carried through with each of the pressure histories presented in Figures 9 through 17. Such analyses lead to the conclusion that the stage is set for the pressure wave to develop by the initial spacial relations of ignition and ullage and the redistributions of the charge that take place during the passage of the ignition front through the powder bed. These factors appear to determine the variable initial rates of pressure rise in the different sections of the charge. No wave would develop if the initial rate of pressure rise was uniform throughout the chamber. The amplitude of the wave which develops appears to be a function primarily of the amount of motion and differential packing of the powder grains which occur during succeeding phases of the wave.

It has been postulated that pressure waves are standing waves, their origin and propagation dependent in part on motion of the powder bed. The question then arises as to the degree to which these acoustic waves are augmented by the powder motion. The answer would appear to hinge on the type of motion which the powder grains experience. If the powder motion is essentially that of discrete particle (grain) motion in a fluid stream with each grain moving essentially independently in response to the forces it experiences in the pressure wave, then the pressure waves can be considered to be fundamentally acoustic waves. On the other hand, if the powder tends to move as a unit mass in a piston-type motion in response to the pressure differentials existing on either side of the mass, then the pressure variations observed in the chamber would not constitute true acoustic waves, though the pressure changes at the ends of the chamber might be equivalent to those produced by an acoustic wave. With this latter type of propellant motion, the period of oscillation of the pressure changes would be a function of the oscillating mass (the total propellant mass) and might be different from the period of an acoustic wave in the same chamber. In the experiments considered here, however, the charge masses have been of an order of magnitude such that, when considered as unit masses oscillating in a closed tube (the gun chamber) their natural periods of oscillation are near that of acoustic waves in the same tube. Thus the question of the type of propellant motion could not be resolved on this basis. However, the powder charge is an aggregate of discrete grains, and considered as such, there would be a tendency for grains to accumulate at the two ends of the chamber under the observed pressure gradients rather than tend to form a compact mass in the center section of the chamber. While both possible modes of propellant motion have been considered in this investigation, no experimental evidence for either mode in favor of the other has been found. The answer may well lie at some intermediate point between the two extremes, and becomes a problem for further investigation if and when successful application of the proposed theory requires a resolution of the problem.

While the present study has been confined largely to a study of the contributions of point of ignition and location and extent of the ullage to the formation of pressure waves, considerable data were reviewed which suggested that other factors may, under some conditions, contribute to the formation of waves. These included ignitability and burning rate of the propellant, temperature of the propellant, velocity of the ignition front through the propellant bed, rate of delivery of ignition gases, density of packing of the charge, and performance of the igniter. These parameters are listed largely on the basis of circumstantial evidence - the presence or absence of waves or the variations in wave amplitudes were observed to accompany variations in the enumerated parameters on a number of test firings. However, it does not appear as unreasonable that variations in most of these parameters could affect wave formation. For example, the greater the velocity of the ignition front through the powder bed, the less time there would be for differences in pressure to develop in different sections of the charge and hence the amplitude of developing pressure wave might be reduced. On the other hand, increased sensitivity of burning rate to pressure would tend to amplify differences in pressure in different sections of the charge and thereby increase the pressure gradient in the chamber. The interdependence of some of these parameters must also be considered. Thus, the velocity of the ignition front may depend on rate of delivery of ignition gases and density of packing of the charge. The performance of the igniter may depend on its temperature, which is normally the same as that of the propellant. It is suspected that the presence or absence of pressure waves at low temperatures under supposedly identical conditions may be, in many cases, the result of variations in the performance of the igniter, such as variation in venting pattern, rather than temperature effects in the propellant itself. Consideration was also given to the effect of the rarefaction wave given off at the base of the projectile on the formation of pressure waves. Calculations indicate that, while this wave may contribute to a pressure gradient in the chamber, its amplitude will be low compared to pressure waves often developed and can not be considered the sole generator of pressure waves.

A concomitant result of this study has been the conclusion that pressure waves are not primary sources of velocity variation in guns. Pressure curves with waves appear to be as reproducible generally as "smooth" pressure curves, and the velocity variance within reproducible groups of pressure curves with waves is of the same order of magnitude as that within reproducible groups of "smooth" curves. The idea that pressure waves increase velocity variation seems to have originated in the practice of classifying pressure curves as either "smooth" or "rough" and including in the "rough" group all curves exhibiting pressure waves irrespective of the amplitude of the waves. This practice results in comparing the velocity variation in a homogeneous group with that in a nonhomogeneous group, and greater variation in the latter group is to be expected. If pressure curves are classified in groups on the basis of the amplitudes of the pressure waves, velocity variation can be expected to be reasonably uniform from group to group. This is not to say, however, that the mean velocities of the several groups will necessarily be comparable. Mean rates of pressure rise and mean maximum pressures tend to increase with increasing wave amplitude and these are usually accompanied by higher velocities.

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(d) BUORD ltr NP9-Reb-1:LHT:mmt of 14 Jul 1952

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2. Gun barrels
I. Hedden, S. E.

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